

Reactor Antineutrino Predictions: Current Status and Expected Improvements

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Snowmass NF09 workshop, Dec. 4. 2020

Outline

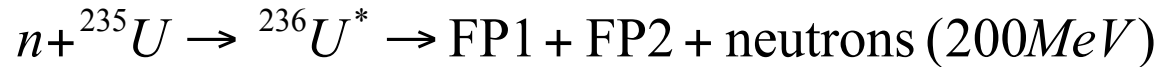
- Introduction & Motivations
- New Calculations for Reactor Antineutrino Spectra
- Reactor Antineutrino Anomaly (RAA)
- Shape Anomaly
- Fuel dependence
- Flux Models
- Expected Improvements
- Concluding Remark

Reactors and Beta Decay

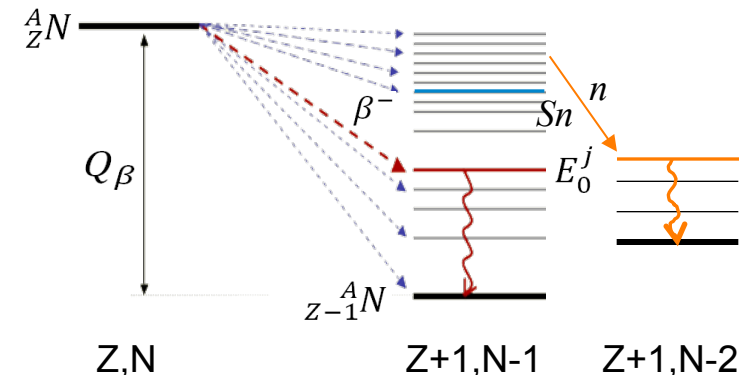
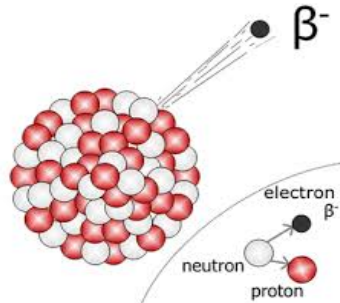
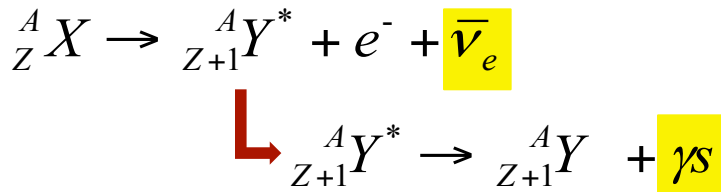
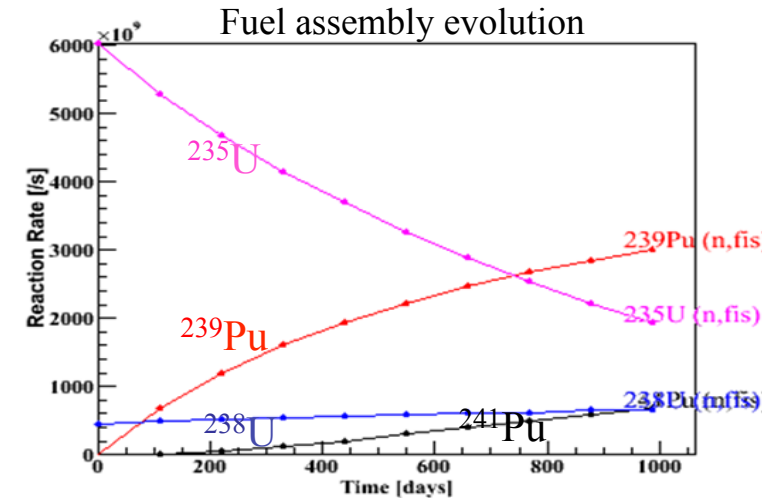
- In Pressurized Water Reactors, thermal power mainly induced by 4 isotopes:

- ^{235}U and ^{238}U in fresh fuel
- Other fissile nuclei (^{239}Pu & ^{241}Pu) created after reactor start by capture and decay processes
- Burn-up effect \Rightarrow unit GWd/t

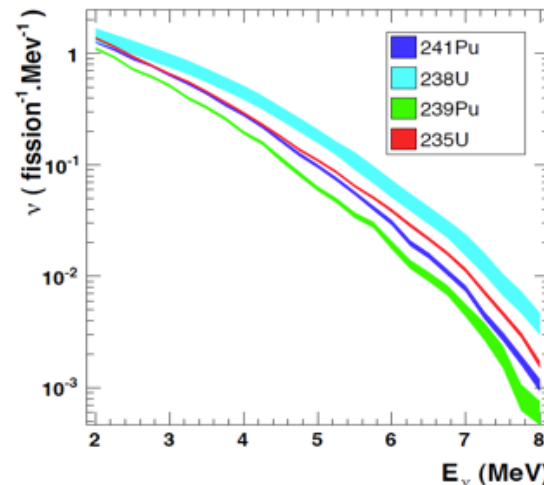
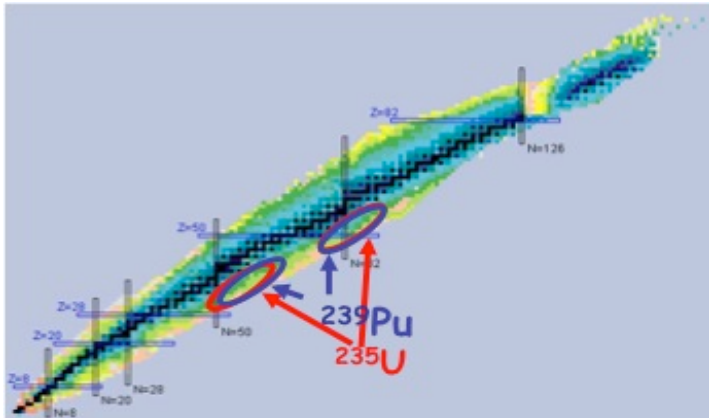
- Fission process gives thermal energy:



- The fission products (FP) after the fissions are neutron-rich nuclei undergoing β and β -n decays:



Antineutrinos for Peace



About 6 antineutrinos
emitted per fission
→ About 10^{21}
antineutrinos/s
emitted by a 1 GW_e
reactor

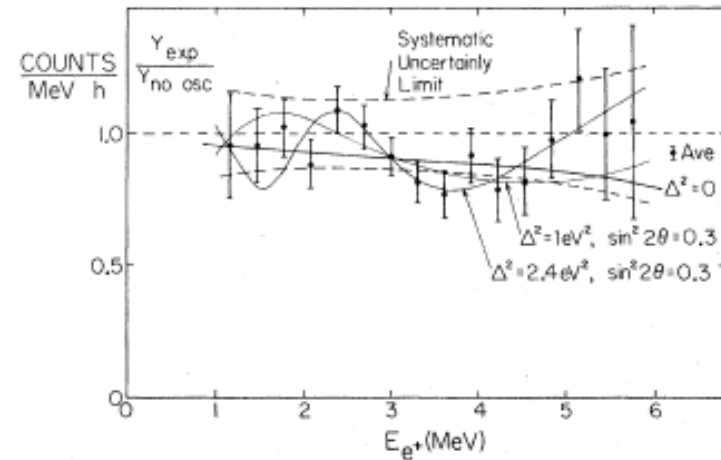
- Use the discrepancy between antineutrino flux and energies from U and Pu isotopes to infer reactor fuel isotopic composition and power
 - ❑ Reactor monitoring, non-proliferation and interest for the IAEA IAEA Report SG-EQGNRL-RP-0002 (2012)
 - ❑ Idea born in the 70s (Mikaelian et al.), demonstrated in the 80s/90s but developed lately

The Summation Method, relying on nuclear data, is the only predictive one for innovative reactors & fuels:

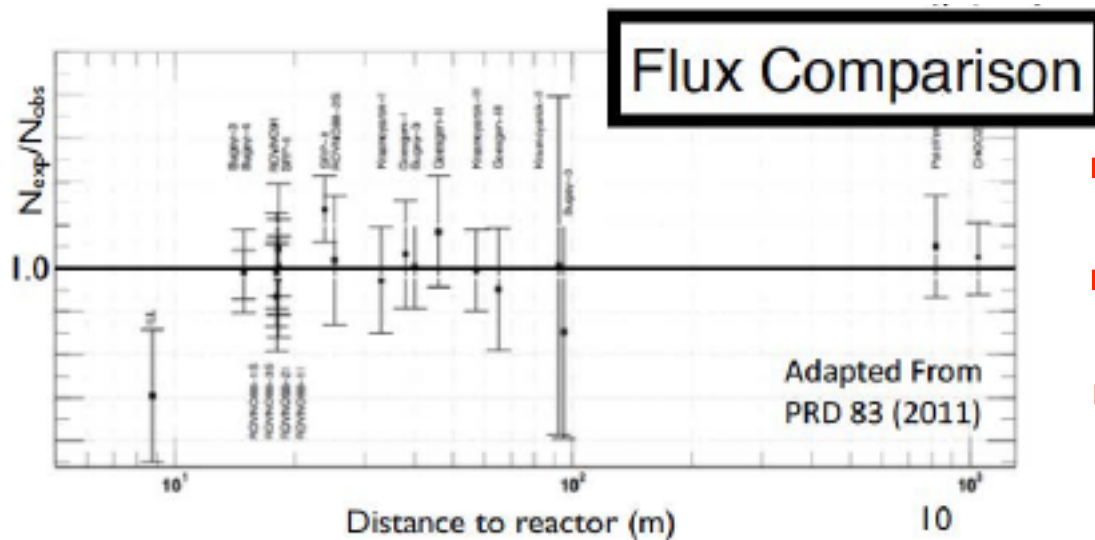
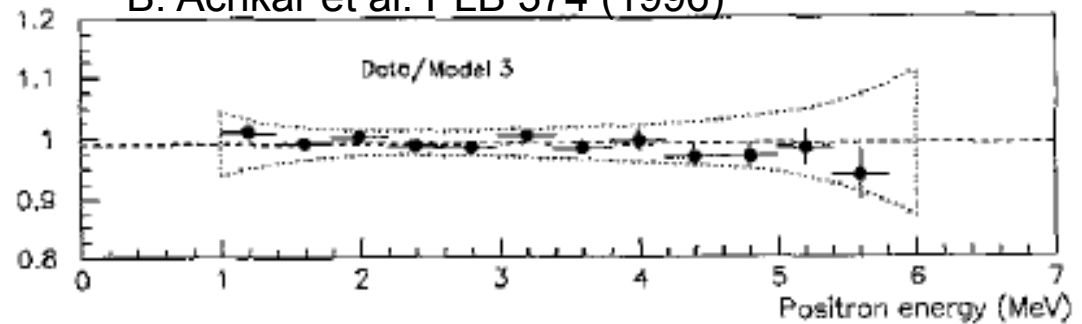
⇒ **The IAEA Nuclear Data Section includes the measurements for reactor antineutrino spectra in their Priority lists** (CRP meetings, TAGS consultant meetings... see P. Dimitriou et al. INDC(NDS)-0676 (2016) **and in 2019 Technical Meeting on Antineutrino Spectra and their Applications, INDC(NDS)-0786)**

How have we arrived there ?

H. Kwon et al. PRD 24 (1981)



B. Achkar et al. PLB 374 (1996)

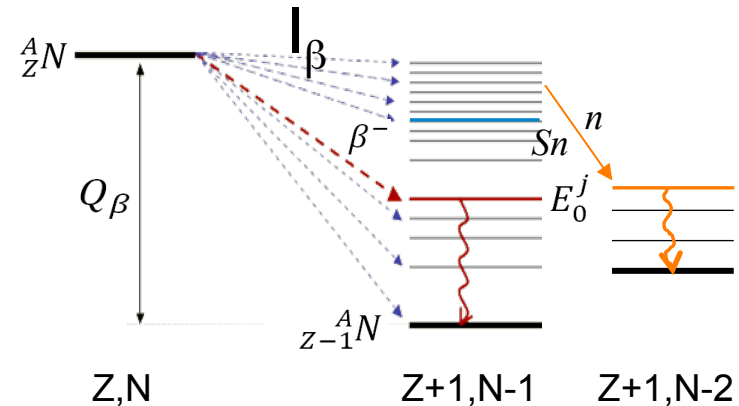
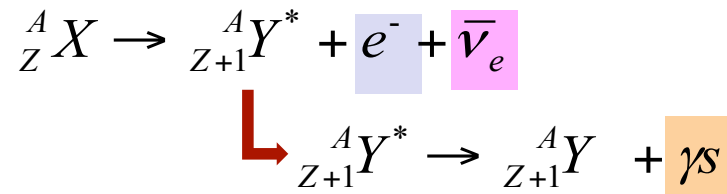


Up to 2011:

- ➔ Ratio of experiments over ILL converted spectra (Schreckenbach et al.) around 1
- ➔ Reactor Antineutrino Spectra well understood
- ➔ ILL converted spectra become the reference

Get Access to the Antineutrino Spectra

- Over the last 40 years, many computations and improvements of the spectra



- Two methods were re-visited in 2011:

- The **conversion of integral beta spectra of reference measured by Schreckenbach et al. in the 1980's at the ILL reactor** (thermal fission of ${}^{235}\text{U}$, ${}^{239}\text{Pu}$ and ${}^{241}\text{Pu}$ integral beta spectra), 2 approaches in good agreement:

 - ✓ Use of nuclear data for realistic beta branches, Z distribution of the branches, 5 fictive beta branches... instead of 30 fictive beta branches
 - ✓ Correction for weak magnetism and finite size effect in both approaches

} H-M model
- The **summation method, summing all the contributions of the fission products** in a reactor core: **only nuclear data : Fission Yields + Beta Decay properties** (several predictions from B.R. Davis et al. Phys. Rev. C 19 2259 (1979), Vogel et al. to Tengblad et al. Nucl. Phys. A 503 (1989)136)

} New SM model

Ingredients to Build Beta and Antineutrino Spectra

$$N_{\beta}(W) = K pW(W-W_0)^2 F(Z,W) L_0(Z,W) C(Z,W) S(Z,W) G_{\beta}(Z,W) (1 + \delta_{WM} W)$$

Where $W = E/m_e c^2$, K = normalization constant,

$pW(W-W_0)^2$ = phase space, to be modified if forbidden transitions with a „shape factor”

$F(Z,W)$ = „traditional” Fermi function

$L_0(Z,W)$ and $C(Z,W)$ = finite dimension terms (electromagnetic and weak interactions)

$S(Z,W)$ = screening effect (of the Coulomb field of the daughter nucleus by the atomic electrons)

$G_{\beta}(Z,W)$ = radiative corrections involving real and virtual photons

δ_{WM} = weak magnetism term

The first results were published in Th.A. Mueller et al, Phys.Rev. C83(2011) 054615

Followed by P. Huber, Phys.Rev. C84 (2011) 024617

BUT many different formulations:

A. C. Hayes and P. Vogel, Annu. Rev. Nucl. Part. Sci. 66, 219 (2016): provide assessment of uncertainties on some of the terms

X.B. Wang, J. L. Friar and A. C. Hayes Phys. Rev. C 95 (2017) 064313 and Phys. Rev. C 94 (2016) 034314,

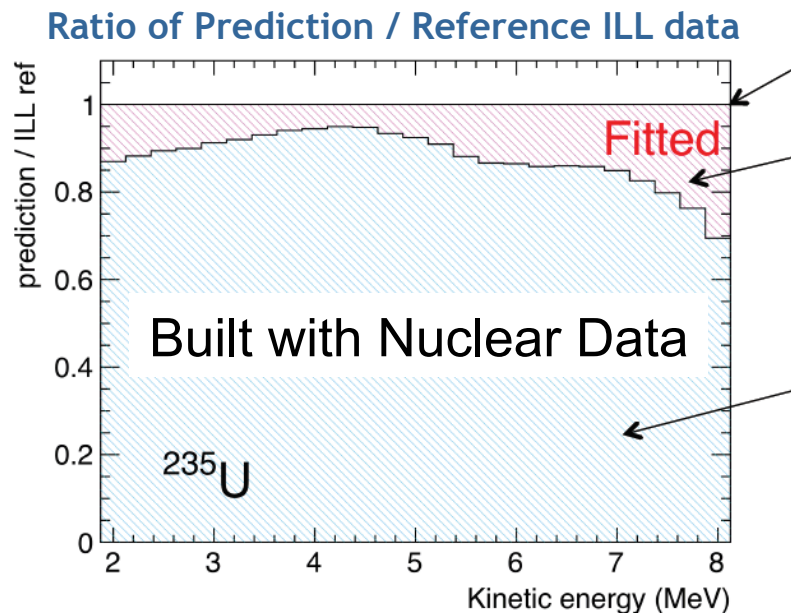
X. Mougeot, Phys. Rev. C 91, 055504 (2015).

L. Hayen, N. Severijns, K. Bodek, D. Rozpedzik, and X. Mougeot, Rev. Mod. Phys. 90, 015008 (2018): with an attempt to perform cross-checks for different formalisms

Reactor Antineutrinos: Converted Spectra

- Calculation of Reactor Antineutrino Spectra from the **conversion of the beta spectra measured by Schreckenbach et al. at the ILL reactor in the 80's**
- Principle: **Fit the beta spectrum shape with beta decay branches** (nuclear data + fictive branches or only fictive branches), taking into account proper Z distribution of the fission products, proper corrections to Fermi theory and a large enough number of beta branches

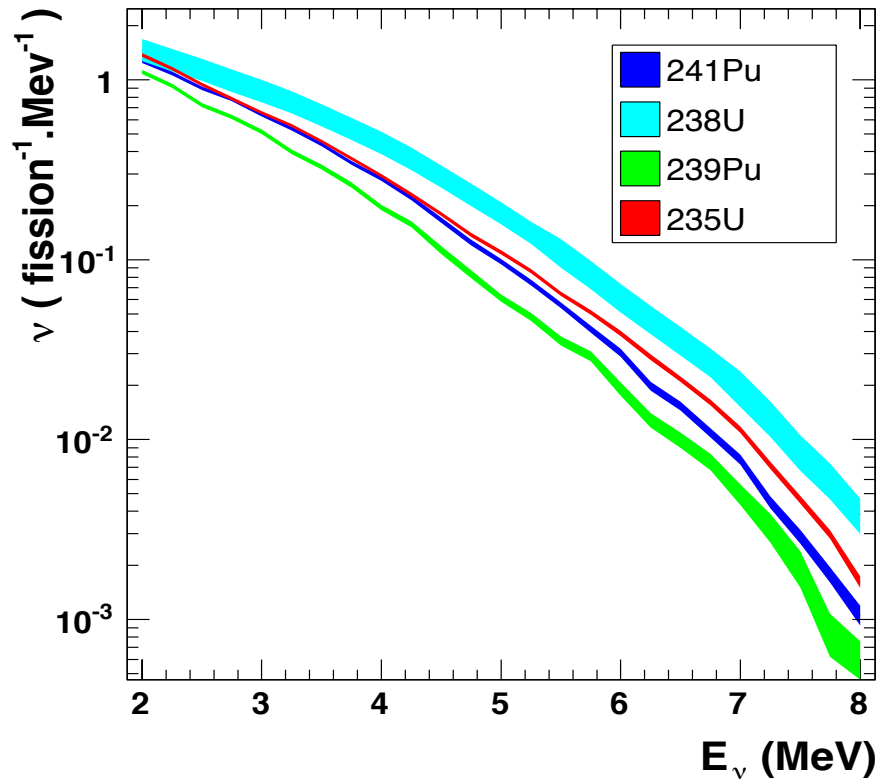
Example: Th.A. Mueller et al, Phys.Rev. C83(2011) 054615:



ILL electron data anchor point

- Fit of residual: five effective branches are fitted to the remaining 10%
- “true” distribution of all known β - branches describes >90% of ILL e data

Revisited Converted Spectra



- **Recent re-evaluations by**
 - ✓ Th.A. Mueller et al, Phys.Rev. C83(2011) 054615.
 - ✓ P. Huber, Phys.Rev. C84 (2011) 024617
- **Off-equilibrium corrections** included (computed with summation method MURE)
- **Summation calculations:** provided the used databases for the conversion + a new ^{238}U prediction

As in 2011: Recent works defining new reference on the neutrino flux prediction for neutrino physics

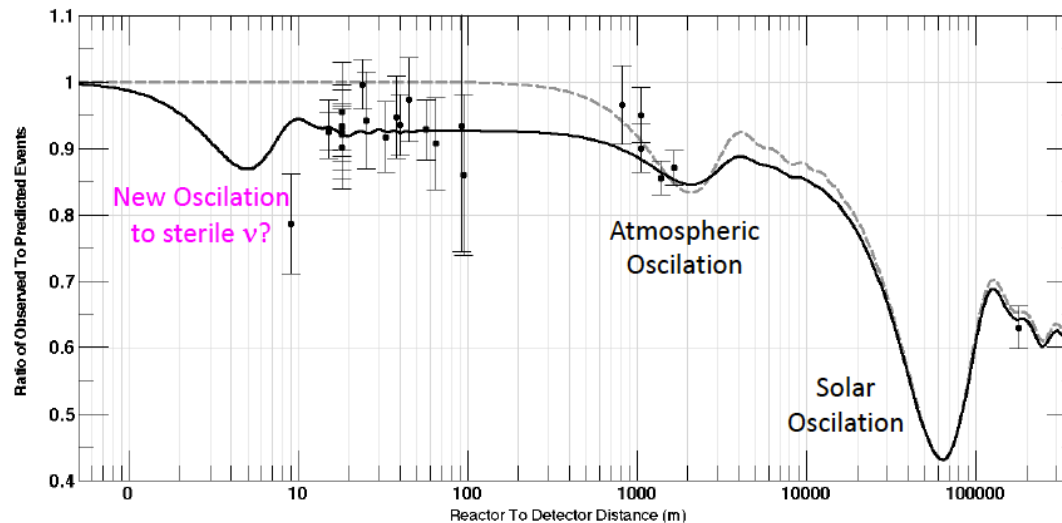
Sterile Neutrino hints ?

Reactor Anomaly:

- ❑ converted ν spectra = $\sim +3\%$ normalization shift with respect to old ν spectra, similar results for all isotopes (^{235}U , ^{239}Pu , ^{241}Pu)
- ❑ Neutron life-time
- ❑ Off-equilibrium effects

2 flavour simple scheme :

$$P_{\text{Osc}} = \sin^2 2\theta \sin^2(1.27 \Delta m^2_{[\text{eV}^2]} L_{[\text{m}]} / E_{[\text{MeV}]})$$



G. Mention et al. Phys. Rev. D83, 073006 (2011)

(3+1)



⇒ Light sterile neutrino state ?

could explain $L=10-100\text{m}$ anomalies, $\Delta m^2 \approx 1 \text{ eV}^2$

Candidate(s) can't interact via weak interaction : constrained by LEP result on 3 families => so can **only exist in sterile form**

Δm_{LSND}^2

ν_e ν_μ ν_τ ν_s



Δm_{atm}^2



Δm_{sol}^2

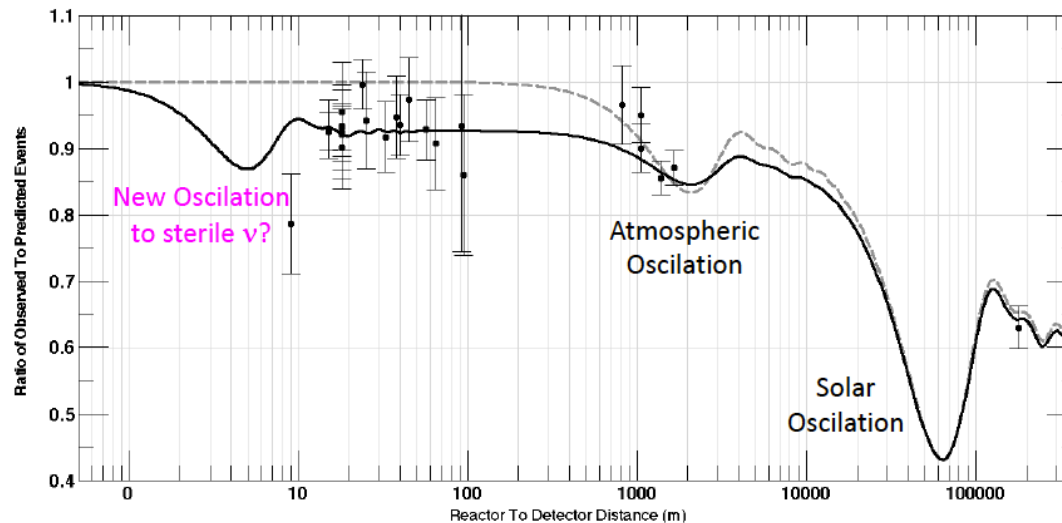
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G. Mention et al. Phys.
Rev. D83, 073006 (2011)

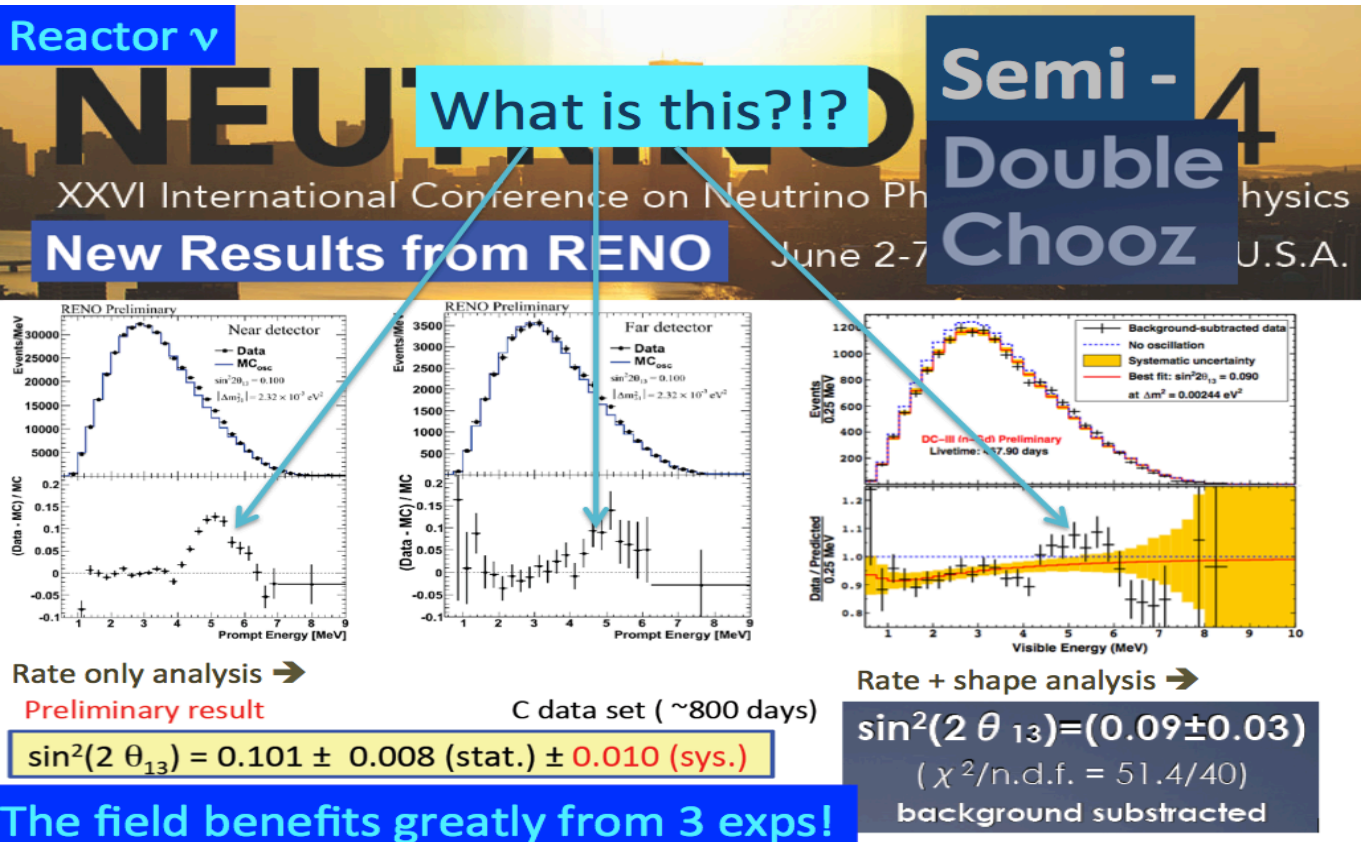
⇒ Looking for **sterile neutrinos** as a potential explanation to the reactor anomaly:
numerous projects: SoLid (UK-Fr-Bel-US), STEREO (France), Neutrino-4 (Russia), DANSS(Russia), PROSPECT(USA), + Mega-Curie sources in large ν detector... (white paper: K. N. Abazajian et al., <http://arxiv.org/abs/1204.5379>.)

The « Shape Anomaly »

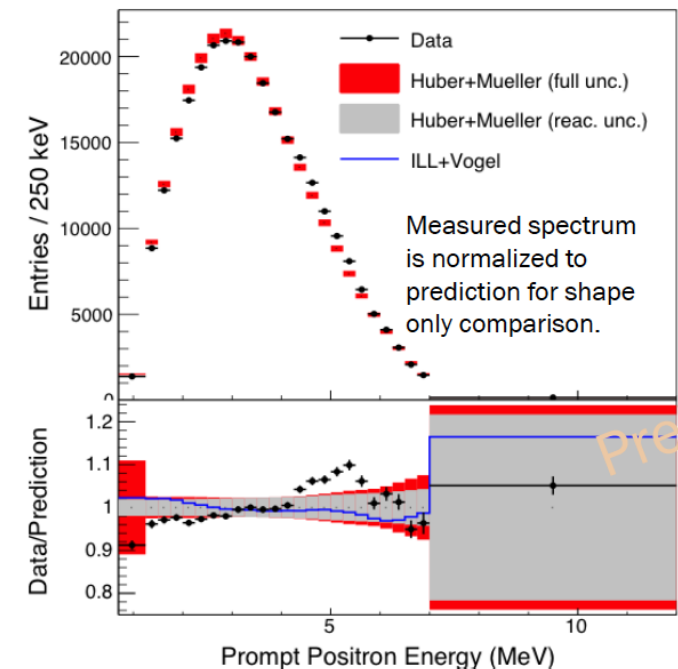
❑ Observation of Shape Distortions w.r.t converted spectra by the 3 large reactor neutrino experiments: Double Chooz, Daya Bay, and Reno:

First communication by Double Chooz & Reno @Neutrino 2014

Followed by Daya Bay @ICHEP2014



✧ Absolute shape comparison of data and prediction: $\chi^2/\text{ndf} = 41.8/21$



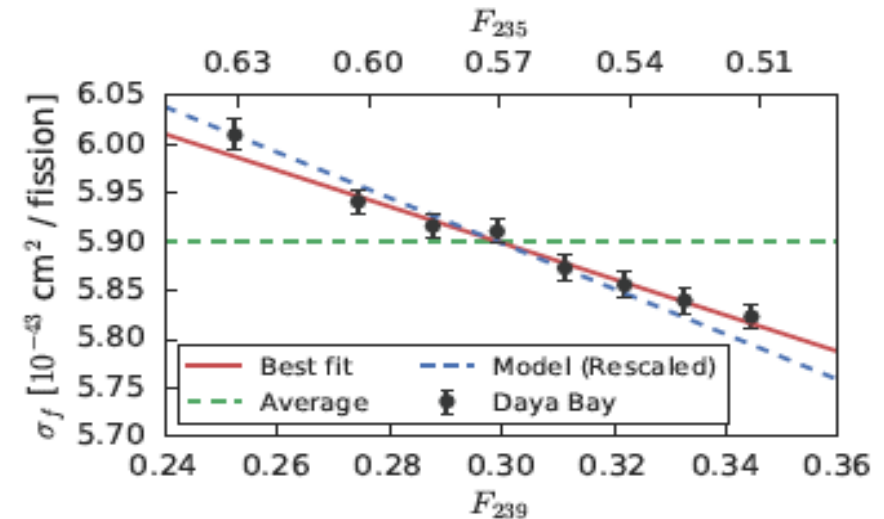
Also observed by the NEOS experiment Phys. Rev. Lett. 118, 121802 (2017)

Context by end of 2017... confirmed in 2019

- 2017: Daya Bay PRL points-out a pb in the converted antineutrino spectra from ^{235}U measured beta spectrum @ILL

An et al. Phys. Rev. Lett. 118 (2017) + APS Viewpoint

Recent papers from DB ([PRL 123 \(2019\) 111801](#)) and RENO (PRL 122 (2019) 232501) reinforce the conclusions



- ⇒ Deficit in detected antineutrinos compared with predictions depends on the relative fractions of ^{235}U , ^{239}Pu , ^{238}U , and ^{241}Pu in the reactor.
- ⇒ ^{235}U fissions produced 7.8% fewer antineutrinos than predicted
- ⇒ In contrast, the discrepancy = almost zero for ^{239}Pu fissions

- ➡ Putting integral beta measurement of ^{235}U of Scheckenbach *et al.* and sterile neutrinos into question
- ➡ Additional motivation for short baseline neutrino experiments: measurement of ^{235}U antineutrino energy spectrum (opportunity with Highly Enriched Fuel reactors)
- ➡ Need for alternative models to converted spectra

Reactor Antineutrino Flux Models

Converted Spectra: Underestimated Uncertainties

● Additional sources of systematic errors:

- ❑ ILL data = unique and precise reference => Need for a second measurement with similar accuracy to exclude potential systematics on the ILL data normalization and shape !!!
- ❑ Large uncertainty for Weak Magnetism term: the most uncertain one among the corrections to the Fermi theory !

P. Huber PRC84,024617(2011): could change the normalization of the spectra if very different value...

D.-L. Fang and B. A. Brown, Phys. Rev. C 91, 025503 (2015): The finite size effects and the weak magnetism corrections obtained in Huber's paper for the allowed (GT) decays are estimated to give a reduction in the number of low energy antineutrinos of 2 – 3%.

- ❑ Impact of the conversion method itself ? Quoting A.C. Hayes: depending on the adopted average effective Z distributions used in the fit of the ILL spectra, converted spectra could vary easily by 5%

- ❑ Treatment of forbidden decays => could change normalization & shape of spectra:

A. Hayes et al. Phys. Rev. Lett. 112, 202501 (2014),

D.-L. Fang and B. A. Brown, Phys. Rev. C 91, 025503 (2015),

X.B. Wang, J. L. Friar and A. C. Hayes Phys. Rev. C 95 (2017) 064313 and Phys. Rev. C 94 (2016) 034314,

L. Hayen et al. Phys. Rev. C 031301(R)(2019)

J. Petkovit, T. Marketin, G. Martinez-Pinedo, N. Paar ArXiv:1903.06192 [nucl-th]

Yu-Feng Lic and Di Zhan, arXiv:1904.07791 [nucl-th]

The Summation Method & γ Measurement Caveat

- SM independent from the integral measurement of Schreckenbach et al. @ ILL. Spectra can be computed with the SM, for one isotope k:

$$S_k(Z, A, E) = \sum_{fp=1}^{N_{fp}} A_{fp} \times \sum_{b=1}^{N_b} I_{\beta_{fp}}^b \times S_{fp}^b(Z_{fp}, A_{fp}, E_{0fp}^b, E)$$

Caveat: totally rely on modern nuclear DB and their biases!

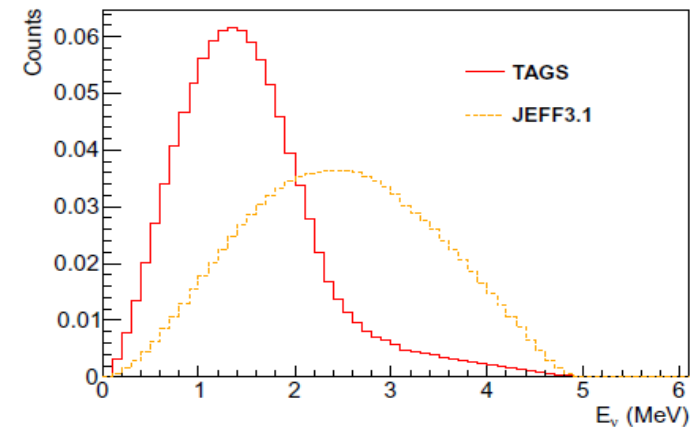


FIG. 1. Illustration of the pandemonium effect on the ^{105}Mo nucleus anti- ν energy spectrum presents in the JEFF3.1 database and corrected in the TAGS data.

- **Incomplete or biased nuclear decay schemes:** overestimate of the high-energy part of the FP β spectra
- Phenomenon commonly called « **pandemonium effect**** » ** J.C.Hardy et al., Phys. Lett. B, 71, 307 (1977)
- Solution is **TAGS measurements** (Total Absorption γ -ray Spectroscopy)
- **Reduced list of contributors and priority lists for new measurements established independently by 2 SM models, in agreement**

A. Sonzogni et al. Phys. Rev. Lett. 116, 132502 (2016), A.
A. Sonzogni et al. PRL 119, 112501 (2017), PRC 98
041323(2018) (2018)

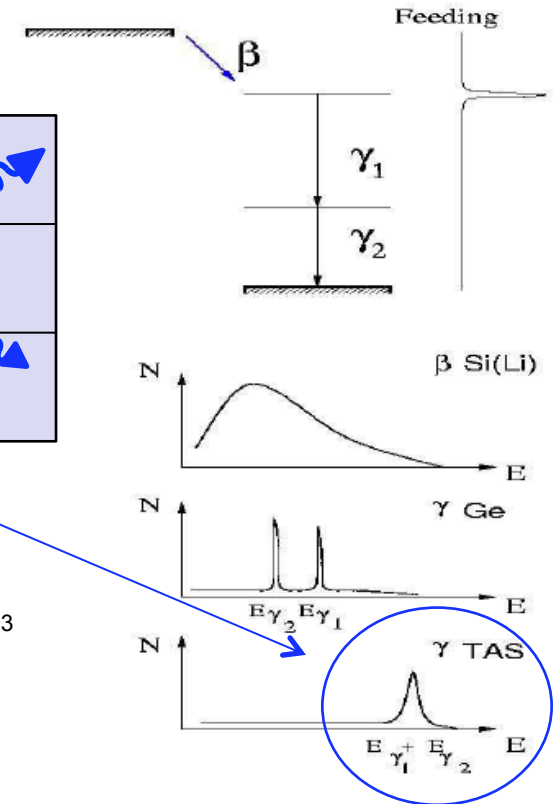
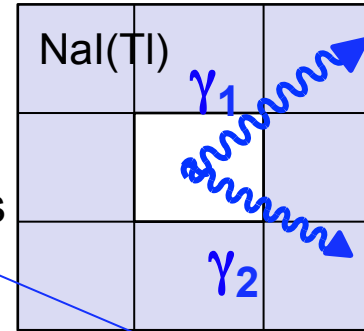
M. Fallot et al. PRL 109 (2012) 202504
A.-A. Zakari-Issoufou et al. PRL 115, (2015) 102503
P. Dimitriou et al. INDC(NDS)-0676 (2016)

- ➡ **Expected distortion of the antineutrino energy spectra computation with SM**
- ➡ **Assumed level of uncertainty in Mueller et al. 2011: 10-15%**

TAGS: a Solution to the Pandemonium Effect

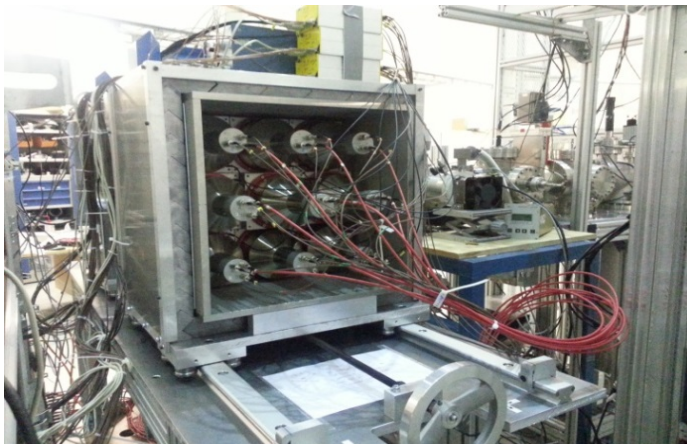
● Total Absorption γ -ray Spectroscopy(TAGS)

- ❑ A TAS is a **calorimeter**
- ❑ It contains big crystals **covering 4π**
- ❑ Instead of detecting the individual gamma rays, absorbs the full gamma energy released by the gamma cascades in the β -decay process



● 2 TAGS campaigns at IGISOL@Jyväskylä:

- ❑ DTAS detector



V. Guadilla et al., NIM A910 (2018) 79

- ✓ 16-18 NaI(Tl) crystals of $15 \times 15 \times 25 \text{ cm}^3$
- ✓ Individual crystal resolutions: 7-8%
- ✓ Total efficiency: 80-90%
- ✓ Coupled with plastic scintillator for β

M. Fallot et al. PRL 109,202504 (2012), **SM-2012**

A.A. Zakari-Issoufou et al. PRL 115, 102503 (2015), **SM-2015**

E. Valencia et al., PRC 95, 024320 (2017) + S. Rice et al. PRC 96 (2017)014320 **SM-2017**

V. Guadilla et al. PRL122, (2019) 042502 **SM-2018**

Systematic error improvement: ~20 measured nuclei of interest for antineutrino spectra

Our IBD Yield Calculation Including TAGS vs DB

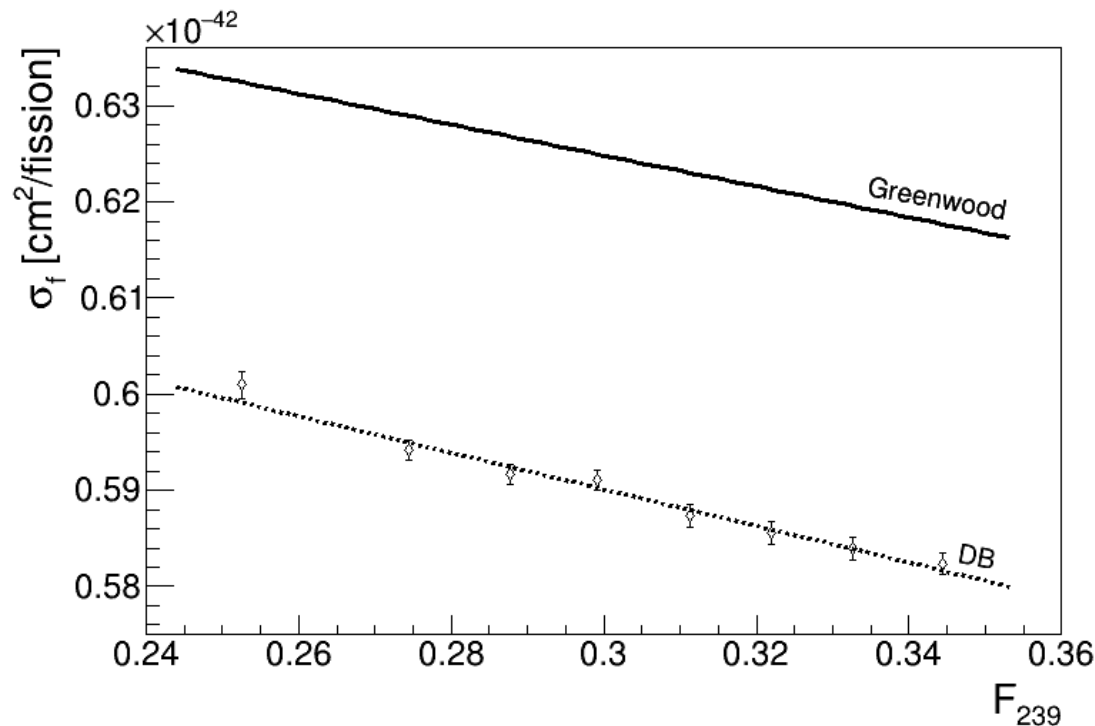
- The IBD yields dependency with F_{239} including TAGS data published in 2012, 2015, 2017 and 2019 has been calculated using our summation calculation

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E. Valencia et al., PRC 95, 024320 (2017) + S. Rice et al. PRC 96 (2017) 014320 **SM-2017**

V. Guadilla et al. PRL 122, (2019) 042502 **SM-2018**



- Impact of the inclusion of the TAGS data (Pandemonium free):
 - ⇒ **Systematic reduction of the detected flux**
 - ⇒ **Systematic reduction of the discrepancy with Daya Bay results**
 - ⇒ Implies an increasingly smaller discrepancy with the inclusion of future TAGS data, **leaving less and less room for a reactor anomaly.**

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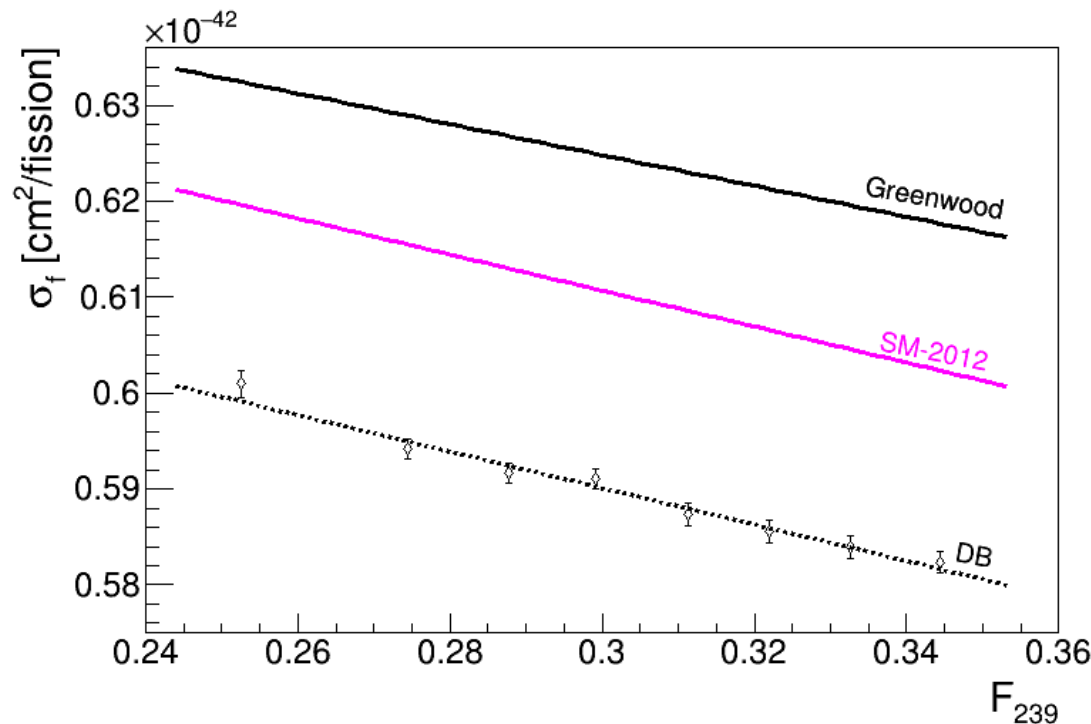
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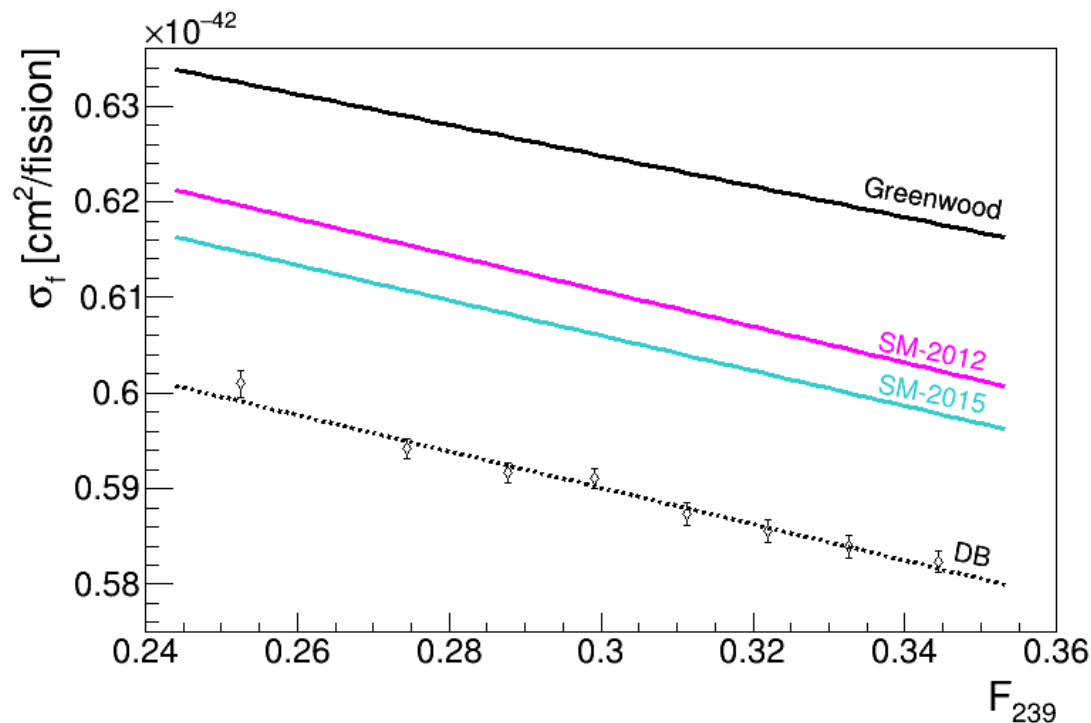
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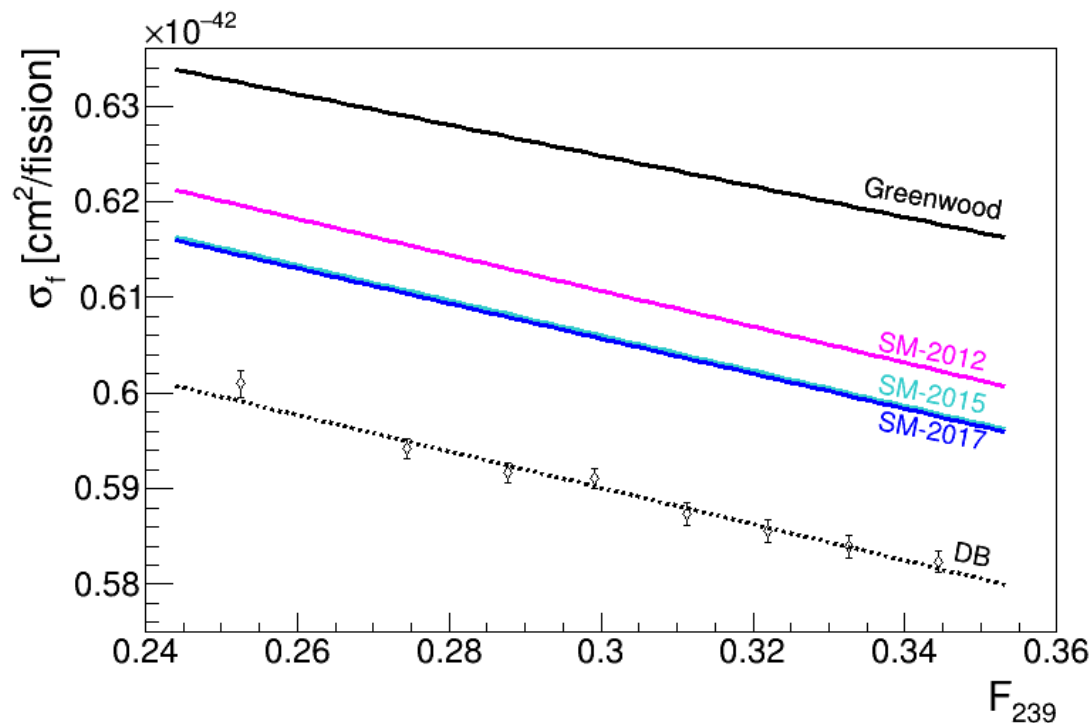
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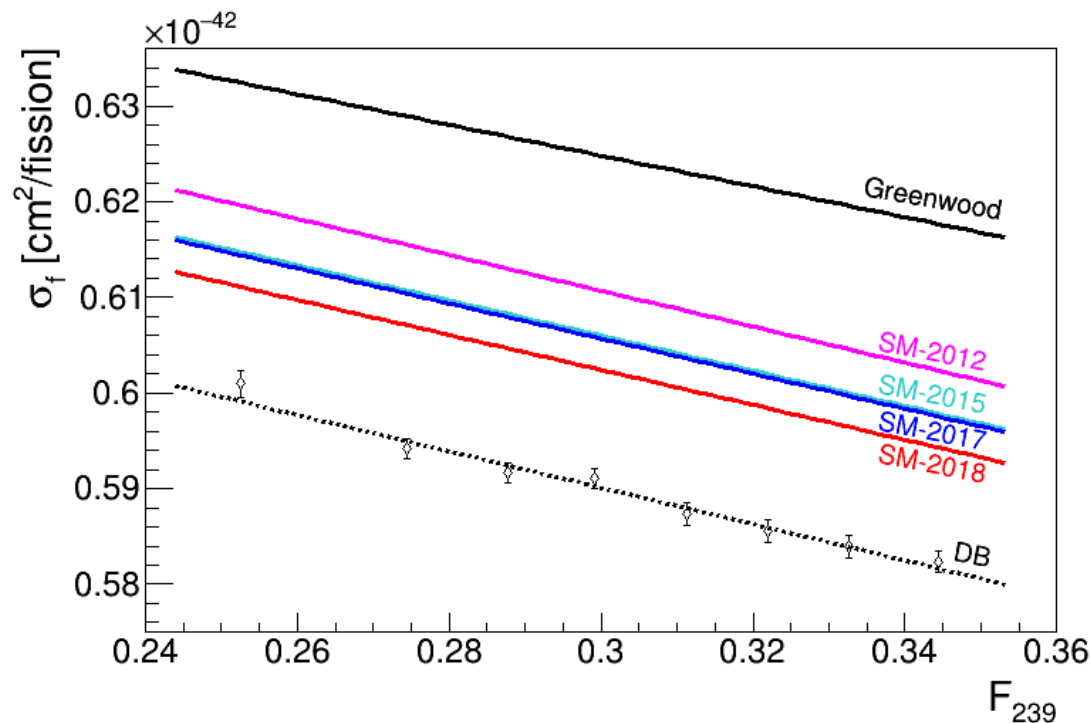
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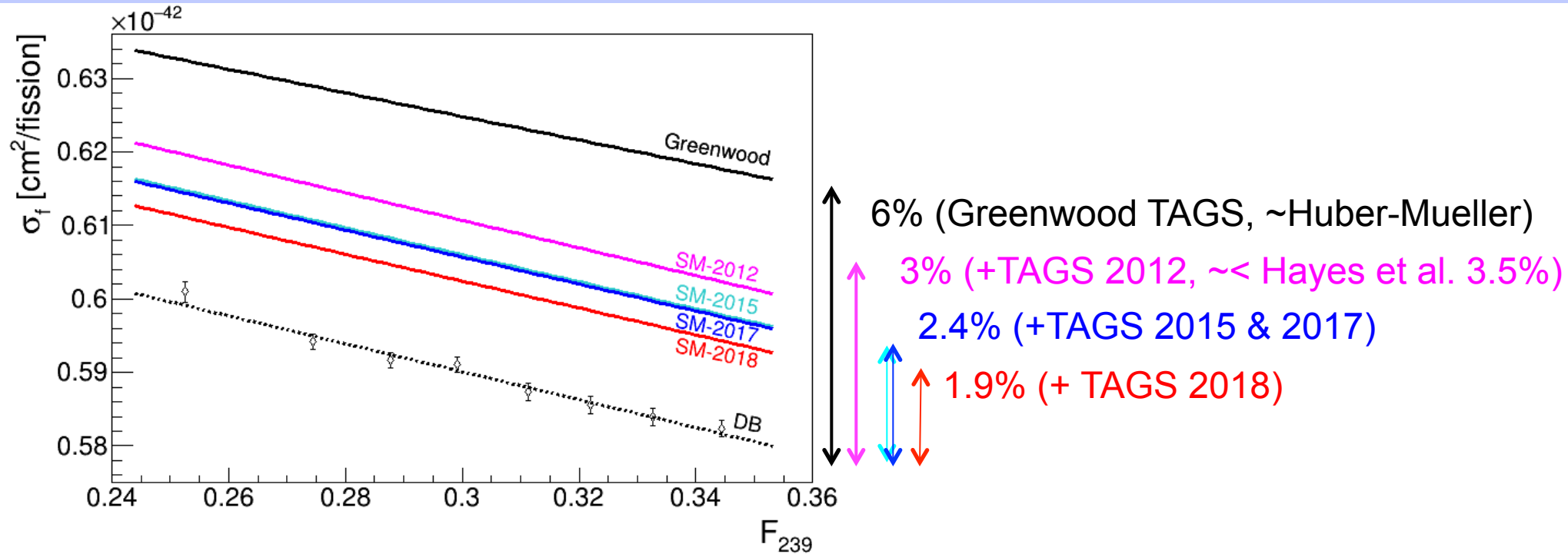
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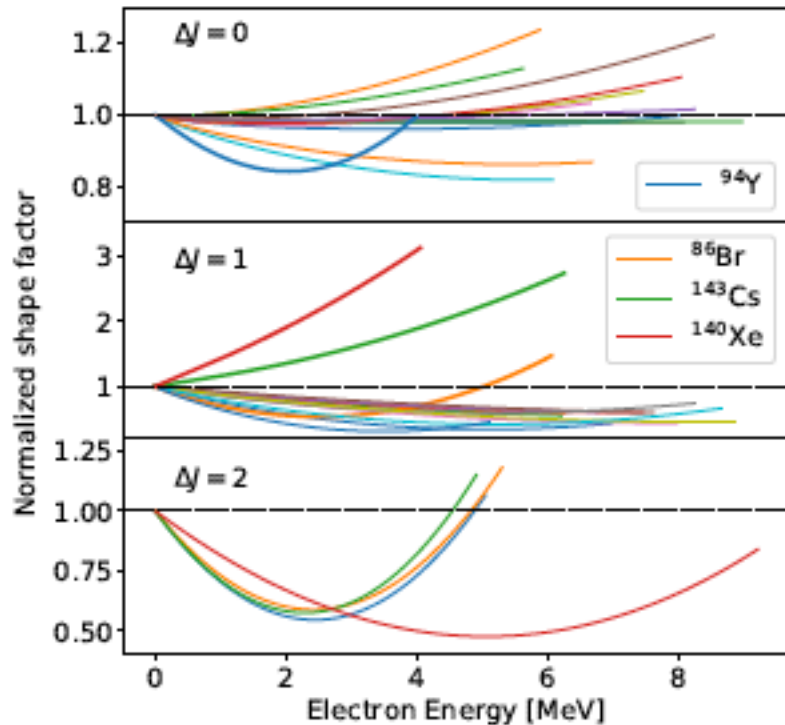
Our IBD Yield Calculation Including TAGS vs DB



- The remaining discrepancy with the Daya Bay flux **reduces to only 1.9%**
- Even with the inclusion of the 2018 TAGS data, the **bump is still there** i.e. for the moment, it still **cannot be explained** by ingredients of the nuclear databases.
- **With the SM model, no huge discrepancy in the flux w.r.t. DB for one specific fissioning nucleus: 2.5-3% for ^{235}U and ^{239}Pu (contrary to H.-M.) and about 1% for ^{238}U and ^{241}Pu**

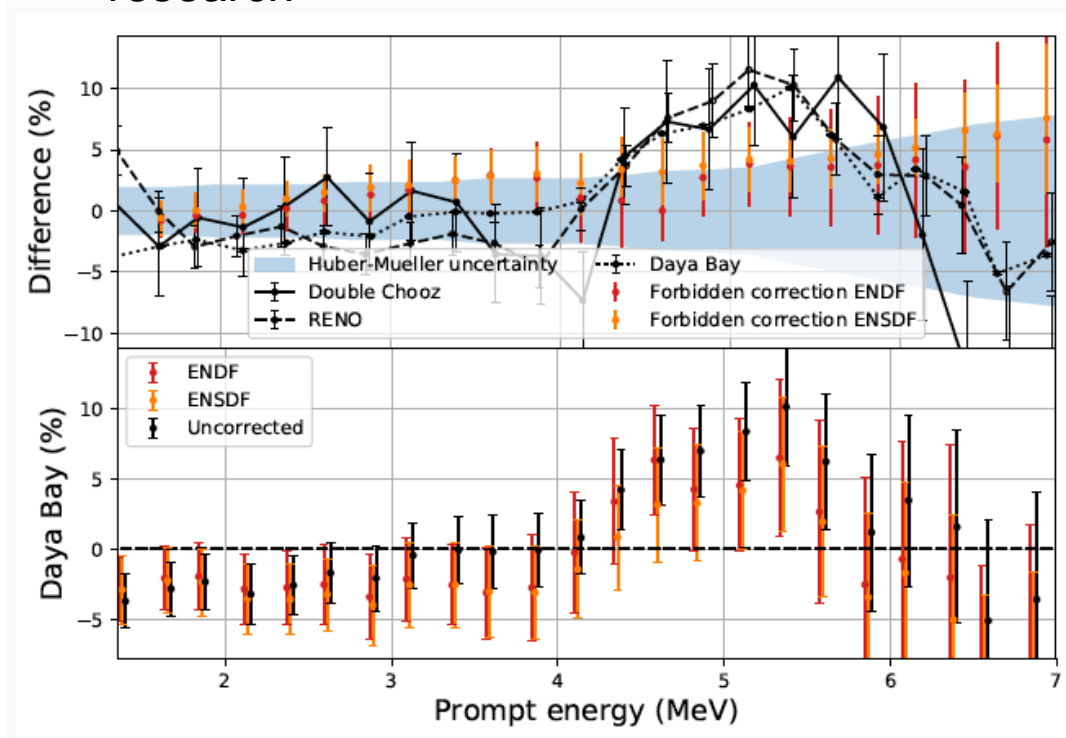
Explanation for the shape anomaly ?

Calculation of the shape factors for forbidden decays: discrepancies among models, largest shape factors from L. Hayen et al.



L. Hayen et al., PRC.100.054323

Bump significantly mitigated, still further research



L. Hayen et al., PRC 99 (2019) 031301(R)

➔ Measurements of the shape factors for the most important forbidden decays are needed to disentangle models, and understand the shape anomaly

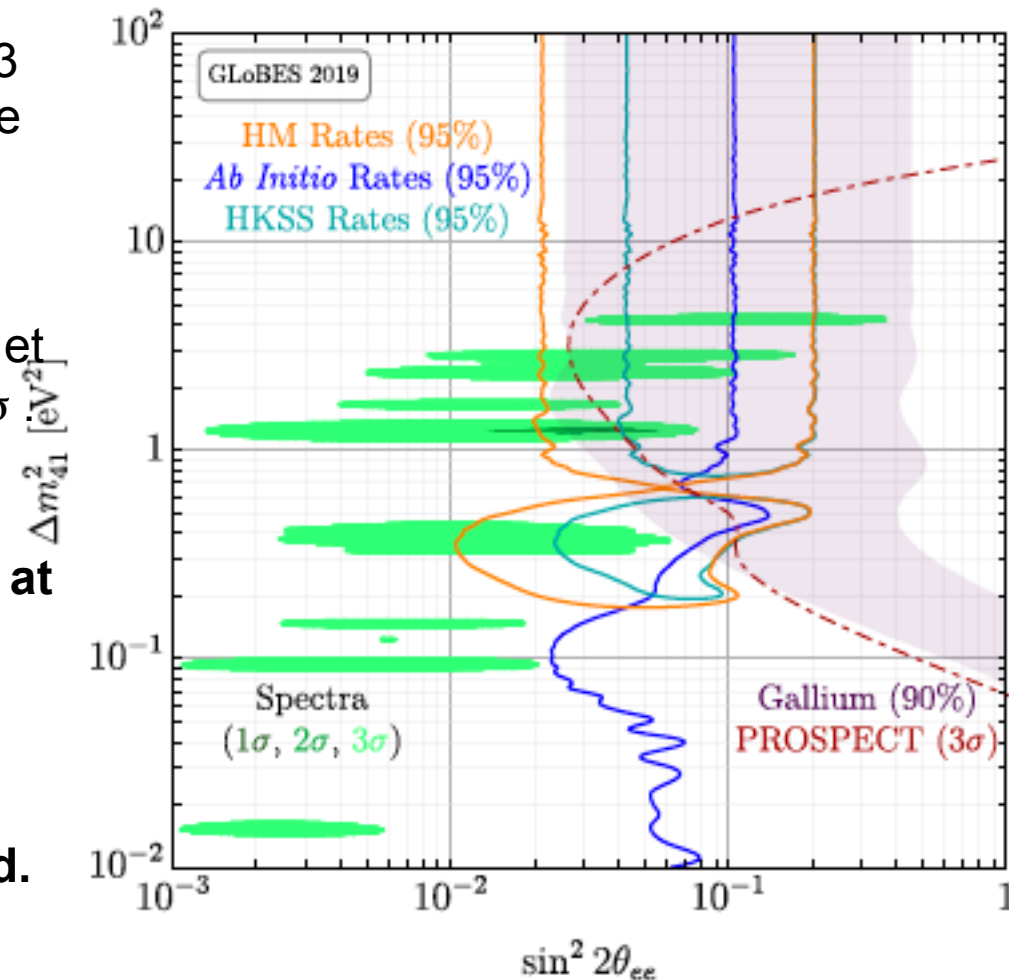
Models in Global Analysis

Reanalyzed the global reactor $\bar{\nu}_e$ data set using 3 reactor antineutrino flux predictions: HM, Estienne et al., Hayen et al.

Estienne et al. 's calculation decreases the significance from 2.3σ to 0.95σ , whereas Hayen et al.'s calculation increases the significance to 2.8σ

Shape anomaly still robust with respect to varying the flux model and is found to persist at the 3.1σ level.

Null results from current reactor experiments would leave a significant fraction of the currently favored parameter space unexplored.



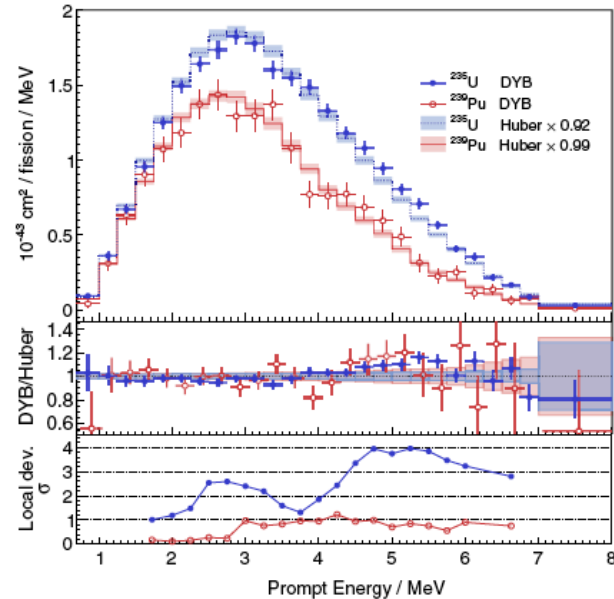
J. M. Berryman and P. Huber Phys. Rev. D 101, 015008 (2020)

Other global analyses in Giunti et al. PRD 99, 073005 (2019), A. Diaz et al.

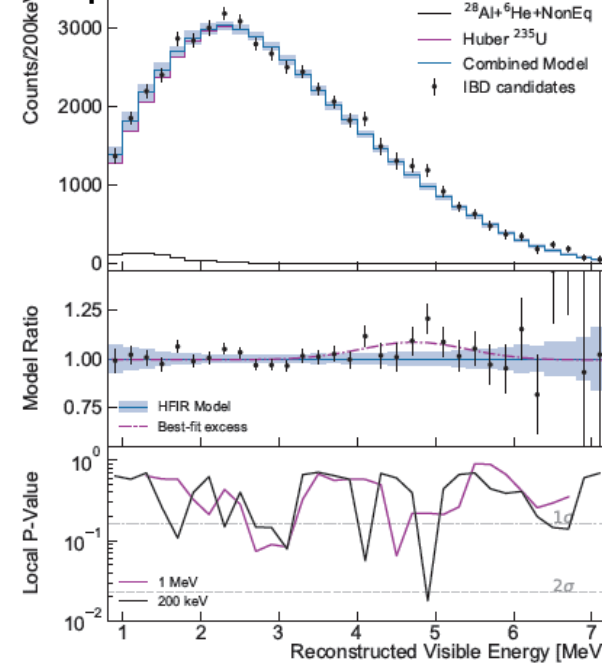
[arXiv:1906.00045v3](https://arxiv.org/abs/1906.00045v3), S. Boeser et al. PPNPP 111 103736 (2019)

Experimental Results

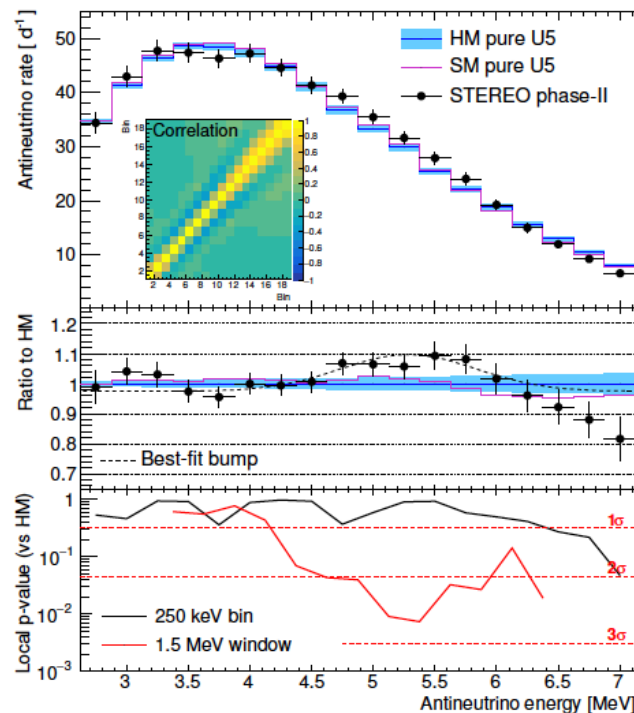
Daya Bay's extraction of ^{235}U and ^{239}Pu spectra: An. et al.
PRL 123 (2019) 111801



Prospect: arXiv:2006.11210

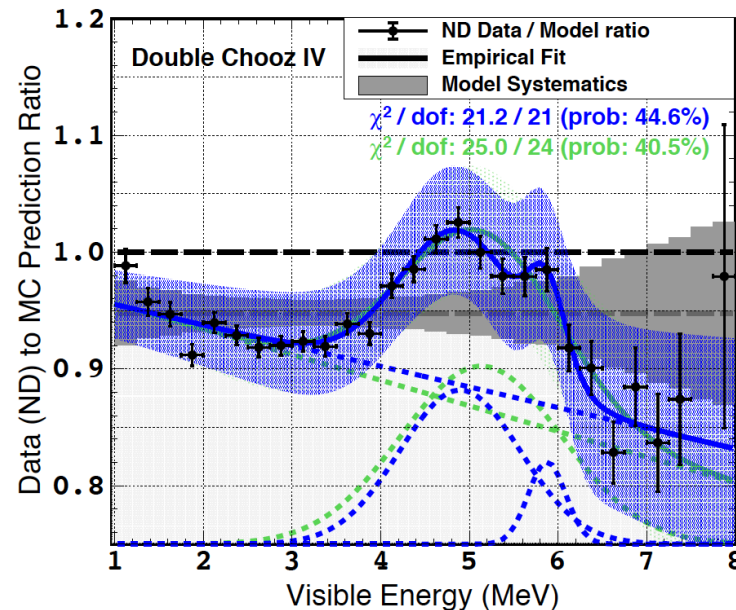


STEREO: arXiv:2010



Two-gaussian fit and slope

Double Chooz Nature Physics



Reno arXiv:2010

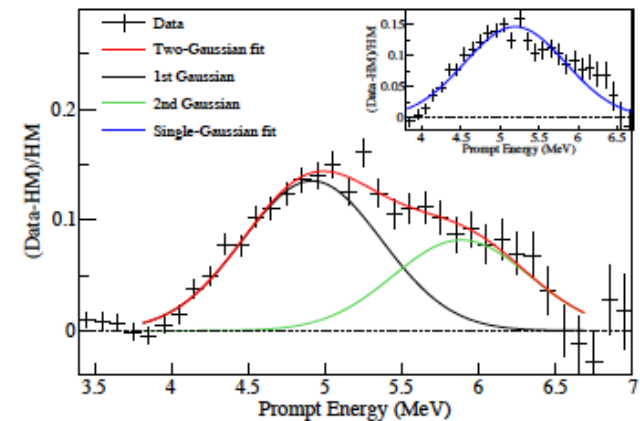


FIG. 4. Two-gaussian spectra obtained from a fit to the measured prompt spectrum in the excess region. The two-gaussian fit is favored compared to a single-gaussian fit shown in the inset. The obtained gaussian spectra peak at prompt energies of 4.9 and 5.9 MeV and with widths of 0.5 and 0.4 MeV, respectively.

Fine Structure in the Antineutrino Spectra

Using Summation Method:

« With better resolution and small bin intervals, the contributions from individual nuclides, not captured in the conversion, begin to appear.

Must rely on nuclear databases to understand them »

A. Sonzogni et al. @ AAP2018 proposed that the ν oscillation feature seen in the ratio NEOS/Daya Bay is due to ^{99}Nb , ^{143}La , ^{92}Y , ^{99}Zr .

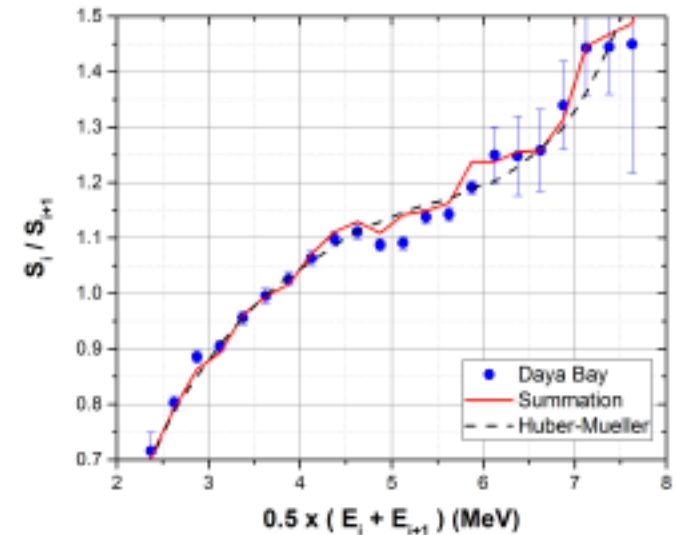


FIG. 4. Ratio of two consecutive IBD spectrum points from the Daya Bay experiment (symbols), Huber-Mueller model (dashed black line) and summation method (full red line). For clarity's sake, the calculated points are connected with a straight line, instead of a step function as in Fig. 3.

A. A. Sonzogni, M. Nino, and E. A. McCutchan PRC 98, 014323

➡ If correct, these features should be seen by other experiments.

➡ The JUNO-TAO experiment, with a very good energy resolution, may allow to perform such identification of individual fission product contributions

Expected Improvements

IAEA Technical Meeting 2019

- Technical Meeting on Antineutrino Spectra and Applications, Organized by the Nuclear Data Section of IAEA April 23-26 2019 – **Report INDC(NDS)786 2019**
- ~30 participants, representatives nearly from all reactor neutrino experiments (Daya Bay, Reno, Juno, Juno-Tao, Double Chooz, SoLid, Prospect, DANSS, Neutrino-4, NEOS, Coherent, Chandler, ...) + representatives from modelling side (theorists, nuclear data specialists) + representatives nuclear experimentalists from US and Europe



INDC(NDS)-0786
Distr. G, EN, ND

INDC International Nuclear Data Committee

Antineutrino spectra and their applications

Summary of the Technical Meeting

IAEA Headquarters, Vienna, Austria
23-26 April 2019

Prepared by

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Summary Conversion– Report INDC(NDS)786 2019

«

- Several publications since 2011 have pointed out that the total uncertainties were significantly underestimated
- The conversion procedure itself suffers from larger uncertainties than expected due to the distribution of the average effective Z of the beta branches used in the fit of the ILL beta spectra.
- There are also large uncertainties in the treatment of high Q -value forbidden non-unique transitions. The effect of these uncertainties is still not well understood.

»

Summary Summation– Report INDC(NDS)786 2019

«

- There has been significant improvement in the Summation Method (SM) calculations which rely heavily on nuclear data for fission yields and fission product decay data.
- A large concerted experimental effort driven by several nuclear physics groups has resulted in a series of targeted Total Absorption Gamma-ray Spectroscopy measurements of a large number of isotopes relevant to anti-neutrino spectra. The new TAGS decay data have led to significant improvement in the quality of the summation.
- There have also been efforts to improve the fission yield data with the works performed by Sonzogni et al. and Schmidt et al.

»

US TAGS measurements: B. C. Rasco et al., Phys. Rev. Lett. 117, 092501 (2016), B.C. Rasco et al. Phys. Rev. C 95, 054328 (2017), A. Fijalkowska et al. Phys. Rev. Lett. 119, 052503 (2017)

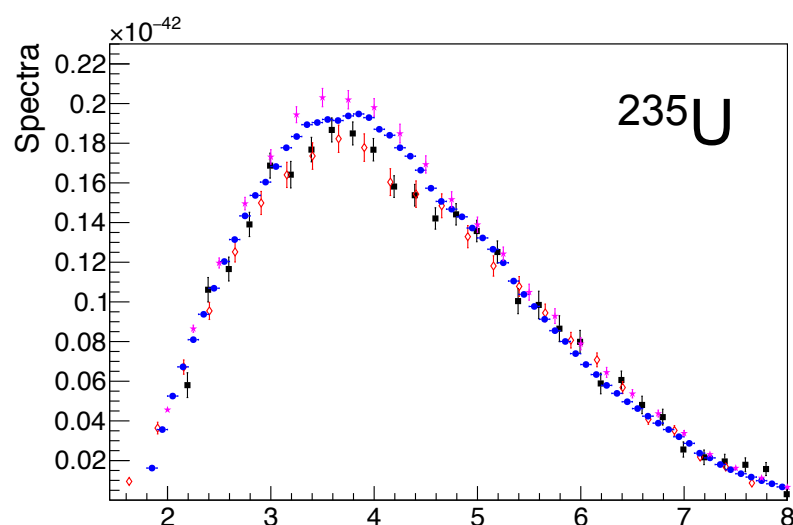
A. Sonzogni et al. Phys. Rev. Lett. 116, 132502 (2016), A. Sonzogni et al. PRL 119, 112501 (2017), PRC 98 041323(2018) (2018)

M. Fallot et al. PRL 109, 202504 (2012), A.A. Zakari-Issoufou et al. PRL 115, 102503 (2015), E. Valencia et al., PRC 95, 024320 (2017), S. Rice et al. PRC 96 (2017) 014320, V. Guadilla et al. PRL 122, (2019) 042502, [M. Estienne et al. PRL 123, \(2019\) 022502](#),

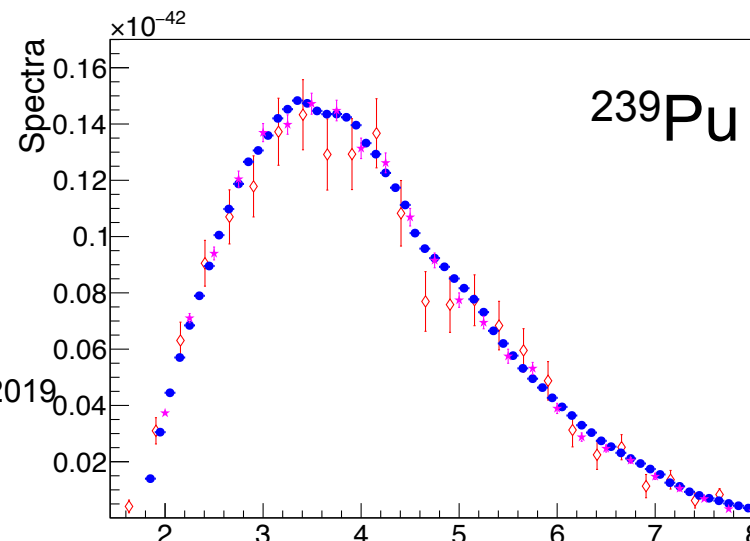
Progress and Achievements

Progress and Achievements

1. A good agreement has now been reached among the two models (CM and SM) for the shape of the antineutrino energy spectra of ^{235}U , ^{239}Pu and ^{241}Pu in the 2 to 5 MeV energy range. The spectral deviation in the 5 to 7 MeV antineutrino energy range observed between measurements and model predictions still cannot be explained.
2. The IBD flux predicted by the updated SM calculations is closer to the measured one compared to the SM predictions performed in 2011. The disagreement between SM flux and that measured by the global flux experiments has dropped from 7% to between 2 and 3% [33, 34].
3. With regards to the rate, the ^{235}U IBD yield measured by LEU reactor neutrino experiments is found to be lower than the CM prediction, in contrast to what is found for ^{239}Pu . This trend is also reflected in the summation calculations. The slope of the IBD yield as a function of burnup obtained with the SM is also in good agreement with the measured one [33, 34].



- SM – PRL 2019
- ★ HM
- ◇ DB - PRL 2019
- Prospect - PRL 2019



Preliminary. Courtesy M. Estienne (Subatech) (N.B.:no absolute normalisation for SBL experiments yet)

Outstanding Issues and Recommendations:

From the IAEA Report (2019):

- Obtain realistic estimates of the uncertainties in the SM. The propagation of uncertainties associated with the decay data and the fission yields on the summation method spectra is being investigated for the effect of uncertainty correlations.
- Improve with more TAGS results,
- Measurement of electron shapes
- Improve the treatment of forbidden non-unique shape factors of the beta decay spectra.
- Improve fission yields data
- Provide an assessment of the published values of the different sub-contributions to the total uncertainties of the conversion models
- Improve the predictive power of nuclear models for the beta decay or the fission process

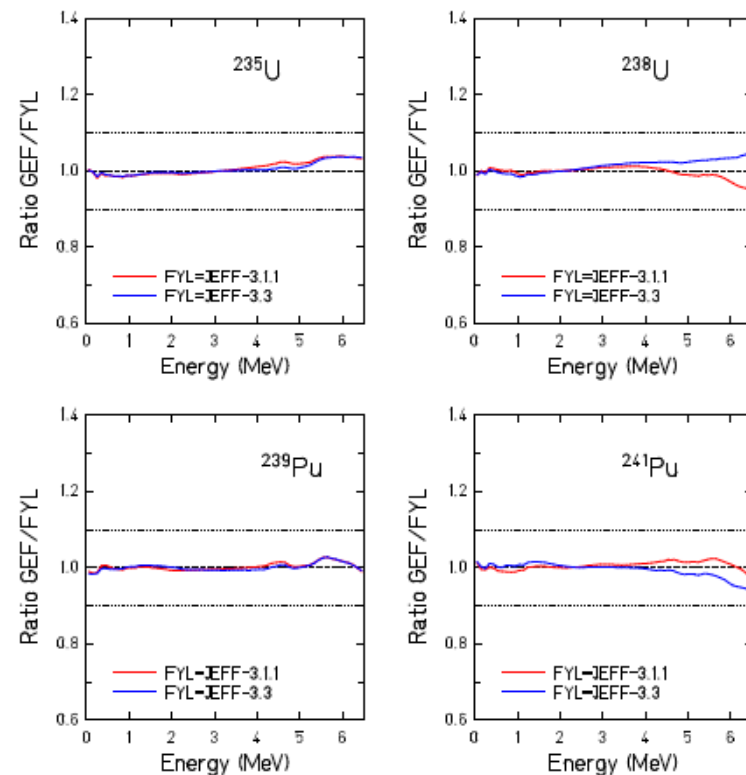
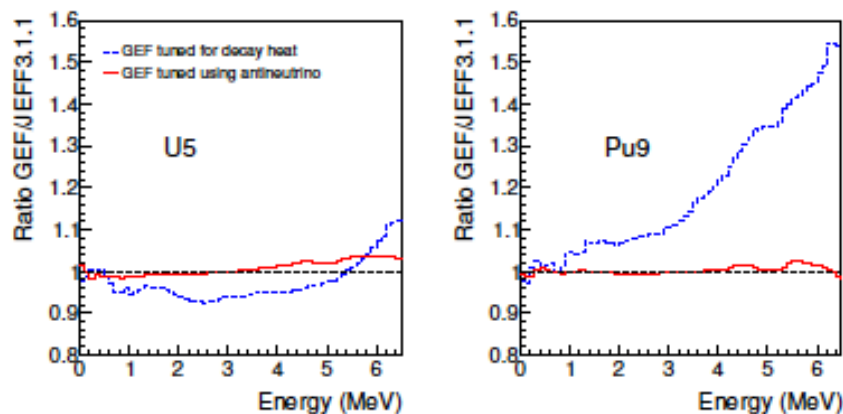
About The SM uncertainties

- At least 2 teams work on their estimate using the GEF code.
- Some preliminary results **presented by A. Sonzogni at IAEA meeting 2019**, using the GEF correlation matrix among fission yields coupled to JEFF3.3 yield uncertainties, showing that these correlations are mandatory

Nucleus	Summation Yield	Sum. Δ Yield	Sum. Δ yield No Corrs.	Yield from theory	H-M Yield	H-M Δ Yield	DB17 Yield	DB17 Δ Yield
^{235}U	6.37	4.59%	1.76%	4.5%	6.69	2.2%	6.17	2.8%
^{238}U	9.69	3.43%	2.04%	14%	10.1	10%		
^{239}Pu	4.39	5.18%	2.08%	8.4%	4.36	4.4%	4.27	6.1%
^{241}Pu	6.25	5.11%	2.36%	15%	6.04	10%		

About The SM uncertainties

- At least 2 teams work on their estimate using the GEF code.
 - ❑ **Estienne et al. collaborate with K.-H. Schmidt** (author of GEF with B. Jurado) for several years with the purpose to use the GEF FY with their uncertainties. First results are:
 - a new version of the GEF code improved thanks to the antineutrino spectral studies
 - an assessment of the experimentally available fission yields with the GEF model showing that the discrepancies btw FY from JEFF3.1.1 and JEFF3.3 are not always understood
 - New predictions compared with the DB flux
 - New predictions of actinide antineutrino spectra for applications



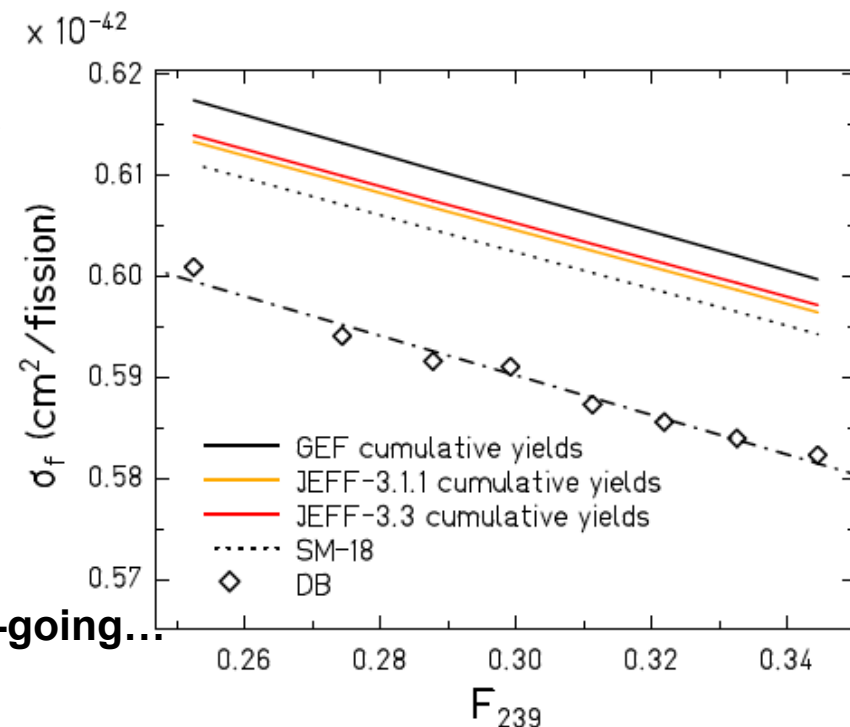
Extensive study of the quality of fission yields from experiment, evaluation and GEF for antineutrino studies and applications
 K.-H. Schmidt, M. Estienne, M. Fallot et al. submitted paper, on arXiv in a few days

FIG. 63. Ratio of the antineutrino spectra calculated with

About The SM uncertainties

- At least 2 teams work on their estimate using the GEF code.
 - **Estienne et al. collaborate with K.-H. Schmidt** (author of GEF with B. Jurado) for several years with the purpose to use the GEF FY with their uncertainties. First results are:
 - a new version of the GEF code improved thanks to the antineutrino spectral studies
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 - New predictions of actinide antineutrino spectra for Applications

FIG. 64. Comparison of the Inverse Beta Decay yields as a function of the fission fraction of ^{239}Pu obtained by the Daya Bay experiment [87] (see text) with summation-model predictions in which the decay data are those of [23] and the fission yields are the cumulative ones from the new version of the GEF code presented here, from the JEFF-3.1.1 database and from the JEFF-3.3 database.



Calculation of uncertainties on SM with GEF is on-going...

Extensive study of the quality of fission yields from experiment, evaluation and GEF for antineutrino studies and applications
K.-H. Schmidt, M. Estienne, M. Fallot et al. submitted paper, on arXiv in a few days

About the Theoretical formulation of the spectra

- **Different and not always compatible prescriptions to calculate the allowed spectra:**
 - ❑ P. Huber, **Phys.Rev. C84 (2011) 024617**
 - ❑ A. C. Hayes and P. Vogel, **Annu. Rev. Nucl. Part. Sci. 66, 219 (2016).**
 - ❑ X.B. Wang, J. L. Friar and A. C. Hayes **Phys. Rev. C 95 (2017) 064313 and Phys. Rev. C 94 (2016) 034314,**
 - ❑ X. Mougeot, **Phys. Rev. C 91, 055504 (2015).**
 - ❑ L. Hayen, N. Severijns, K. Bodek, D. Rozpedzik, and X. Mougeot, **Rev. Mod. Phys. 90, 015008 (2018)**
- **Different formulations of the forbidden shape factors:**
 - ❑ A.C. Hayes et al. **Phys. Rev. Lett. 112, 202501 (2014),**
 - ❑ D.-L. Fang and B. A. Brown, **Phys. Rev. C 91, 025503 (2015),**
 - ❑ L. Hayen et al. **Phys. Rev. C 031301(R)(2019)** and L. Hayen, J. Kostensalo, N. Severijns, and J. Suhonen, **Phys. Rev. C 100, 054323 (2019).**
 - ❑ J. Petkovit, T. Marketin, G. Martinez-Pinedo, N. Paar **ArXiv:1903.06192 [nucl-th]**
 - ❑ **Spectrum-shape method and the next-to-leading-order terms of the β -decay shape factor**, M. Haaranen, J. Kotila, and J. Suhonen, **Phys. Rev. C 95, 024327 (2017)**
 - ❑ **What about D.-L. Fang, Yu-Feng Li and Di Zhan, arXiv:2001.01689: Ab initio calculations of reactor antineutrino fluxes with exact lepton wave functions ?**

An assessment of the theoretical uncertainties associated to the currently used approximations in the spectral formulation is needed

Decay Data News:

- Already some measurements of forbidden non-unique electron spectra + more to come as experiments planned worldwide:
 - S. Al Kharusi *et al.* (EXO-200 Collaboration) **Measurement of the Spectral Shape of the β^- -decay of ^{137}Xe to the Ground State of ^{137}Cs in EXO-200 and Comparison with Theory**, *Phys. Rev. Lett.* **124**, 232502 (2020)
 - **Second-forbidden nonunique β^- decays of ^{24}Na and ^{36}Cl assessed by the nuclear shell model**, Anil Kumar, Praveen C. Srivastava, Joel Kostensalo, and Jouni Suhonen *Phys. Rev. C* **101**, 064304
- **TAGS measurements: latest publications are:**
 - V. Guadilla *et al.* *Phys. Rev. C* **100**, 044305 (2019)
 - **Determination of β -decay ground state feeding of nuclei of importance for reactor applications**, V. Guadilla *et al.* *Phys. Rev. C* **102**, 064304 (2020)
 - **A work that will be useful to assess the TAGS experiment uncertainties, especially on GS feeding determination**

Concluding Remark

A lot of work in perspective !!!

THANK YOU

TAGS COLLABORATION

IFIC Valencia: A. Algora, B. Rubio, J.A. Ros, V. Guadilla, J.L. Tain, E. Valencia, A.M. Piza, S. Orrigo, M.D. Jordan, J. Agramunt

SUBATECH Nantes: J.A. Briz, M. Fallot, A. Porta, A.-A. Zakari-Issoufou, M. Estienne, T. Shiba, A.S. Cucoanes

U. Surrey: W. Gelletly

IGISOL Jyvaskyla: H. Penttilä, Äystö, T. Eronen, A. Kankainen, V. Eloma, J. Hakala, A. Jokinen, I. Moore, J. Rissanen, C. Weber

CIEMAT Madrid: T. Martinez, L.M. Fraile, V. Vedia, E. Nacher

IPN Orsay: M. Lebois, J. Wilson

BNL New-York: A. Sonzogni

Istanbul Univ.: E. Ganioglu

Special thanks to the young researchers working in the project:

L. Le Meur, J.A. Briz, V. Guadilla, E. Valencia, S. Rice, A. - A. Zakari-Issoufou

Discussions with and slides from: A. Algora, J. L. Tain, B. Rubio, S. Cormon, A. Cucoanes, M. Estienne, M. Fallot, L. Giot, A. Porta, T. Shiba, ...are acknowledged

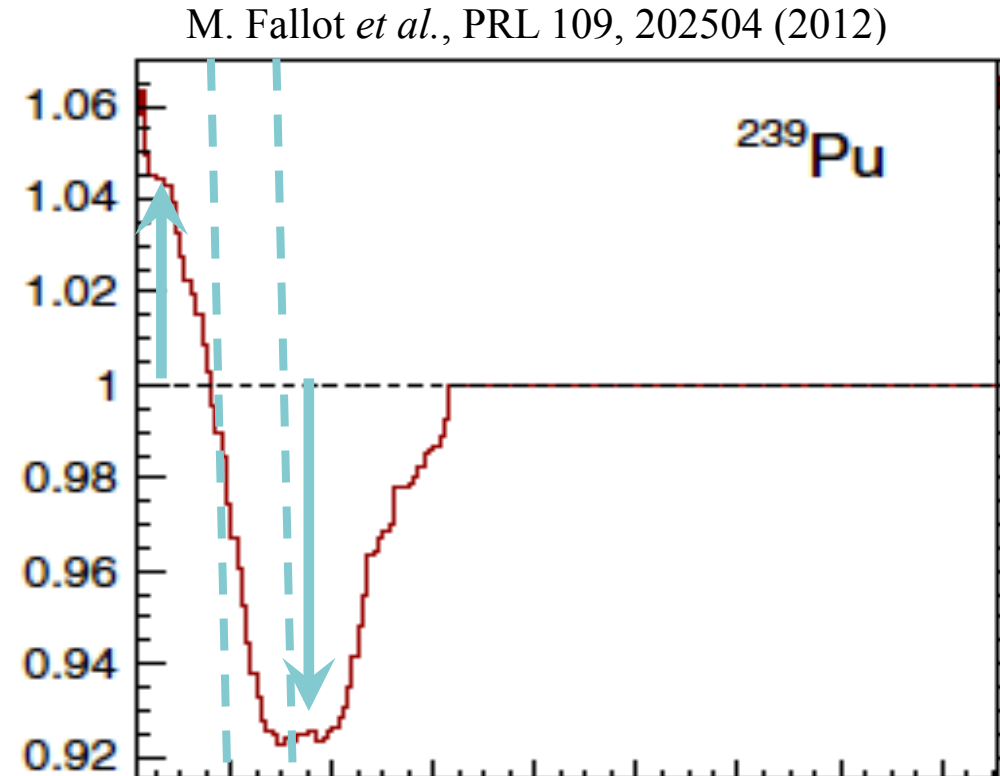
Conclusions & Perspectives

- **High stats Highly Enriched Uranium reactor measurements crucial for understanding**
- **Measurements @ Low Enriched Uranium reactors crucial for disentangling ^{235}U and ^{239}Pu contributions**
- **Still new experimental results from very short baseline experiments expected: more statistics + absolute ^{235}U antineutrino energy spectrum measurement**
- **RAA best fit disfavoured by experiments, but still significant part of the parameter space uncovered**
- **Shape anomaly still not understood by any model, forbidden decays could be a possible explanation`**
 - ❑ Theoretical predictions not in agreement
 - ❑ Need for measurements of shape factors
- **Conversion Method has underestimated uncertainties (method itself, forbidden decays, etc.)**
- **Summation Method has been improved**, thanks to the huge experimental effort with TAGS over a decade, « Bringing the Summation Method to another level » (cf. IAEA INDC(NDS)786 2019) and is only @1.9% from the Daya Bay flux
 - ❑ Still TAGS measurements needed, especially to improve above 4.5-5 MeV
 - ❑ **Calculation of the uncertainties is mandatory**
- Significant improvement in energy resolution proposed by **JUNO-TAO could constitute a benchmark for nuclear data, evidencing the individual components of the fission products**

First Impact of 2010 TAS Data on SM calculations

- Taking into consideration the TAS data of the $^{102,104-107}\text{Tc}$, ^{105}Mo , and ^{101}Nb isotopes measured in 2010 @ Jyväskylä

- ~850 nuclei included
- Noticeable deviation from unity (1.5 to 8% decrease)



Relative Effects of the 2010 TAS data (published 2012) on the Antineutrino Spectra:
typical from Pandemonium: the inclusion of Pandemonium free data increases the
spectrum **before 2-3 MeV** and decreases it above

⇒ Provided the dependence of the IBD cross-section on the energy, this will
impact the IBD yield a lot !

Our New Summation Method: Update of Ingredients

- Decay data updated with **the latest published TAS data = 15 nuclei Pandemonium free**

Nuclei	Model names	Publications
102;104–107Tc, ¹⁰⁵ Mo & ¹⁰¹ Nb	SM-2012 M. Fallot et al. PRL 109, 202504 (2012)	A. Algora et al. PRL 105, 202501 (2010), D. Jordan et al. PRC 87, (2013) 044318
+ ⁹² Rb	SM-2015	A.A. Zakari-Issoufou et al. PRL 115, 102503 (2015)
+ ^{87,88} Br and ⁹⁴ Rb + ⁸⁶ Br and ⁹¹ Rb	SM-2017	E. Valencia et al., PRC 95, 024320 (2017) S. Rice et al. PRC 96 (2017) 014320
+ ^{100,100m,102,102m} Nb	SM-2018 M. Estienne et al., PRL 123, 022502 (2019)	V. Guadilla et al. PRL 122, (2019) 042502 See talk session Nuclear Structure C

- **Then nuclear decay databases in decreasing priority order:**

The Greenwood TAS data set, the experimental data measured by Tengblad et al., experimental data from the evaluated nuclear databases [JEFF3.3](#), [ENDFB-VIII.0](#) and [Gross theory spectra from JENDL2018*](#) and the “Q_β” approximation for the remaining unknown nuclei

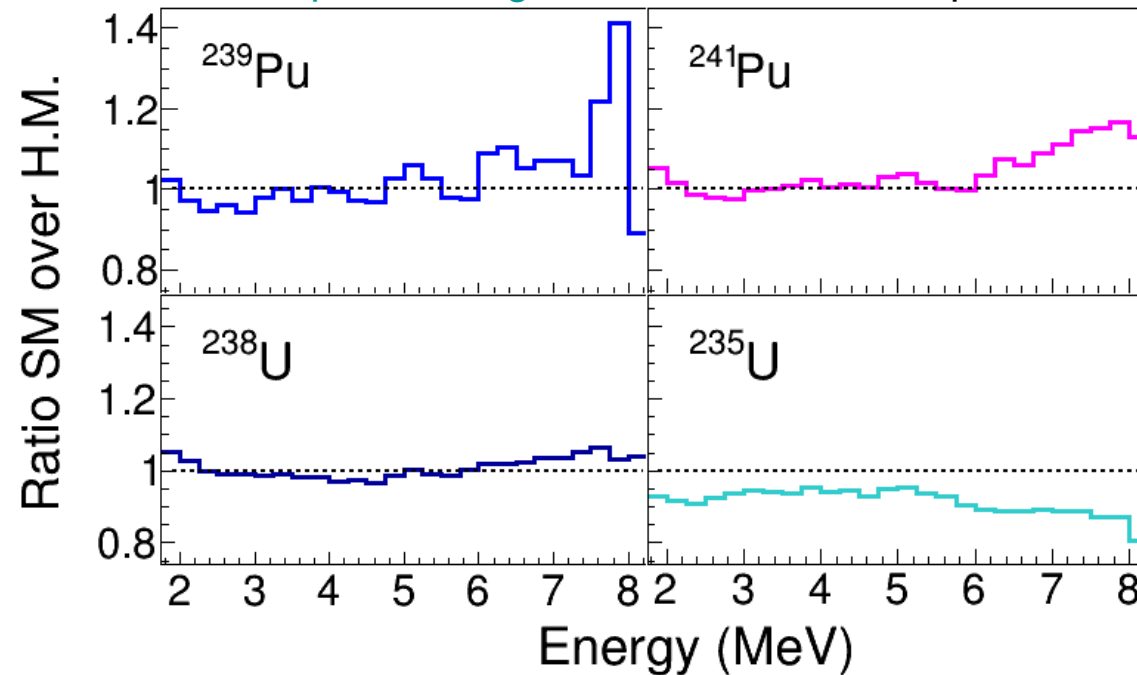
*T. Yoshida, T. Tachibana, S. Okumura, and S. Chiba, Phys. Rev. C 98, 041303(R) (2018).

- **Fission yields database:** [JEFF3.1.1](#)

- Irradiation times with MURE: 12 h for ²³⁵U, 1.5 d for ^{239;241}Pu, and 450 d for ²³⁸U.

Comparison with H-M individual spectra

M. Estienne et al. <http://arxiv.org/abs/1904.09358> accepted in Phys. Rev. Lett.



- The ratios with converted spectra have become flatter up to ~6 MeV compared with SM-2012
 - The normalisation of ^{235}U still disagrees (same as in 2012), confirming Daya Bay's result
 - ^{238}U : ratio w.r.t. Mueller et al 's version of the SM: spectrum remains stable with the update of databases and inclusion of new TAGS results up to ~6 MeV
- ⇒ Overall the SM model shows a fairly good shape agreement with Huber's spectra up to 6 MeV (in the error bars of the converted spectra in this energy range, except for ^{239}Pu)
- ⇒ The energy range matters indeed, because the antineutrino data are also more uncertain above 6 MeV

« Robustness » of the prediction

Table extracted from Mueller et al. Phys. Rev. C 83, 054615 (2011)

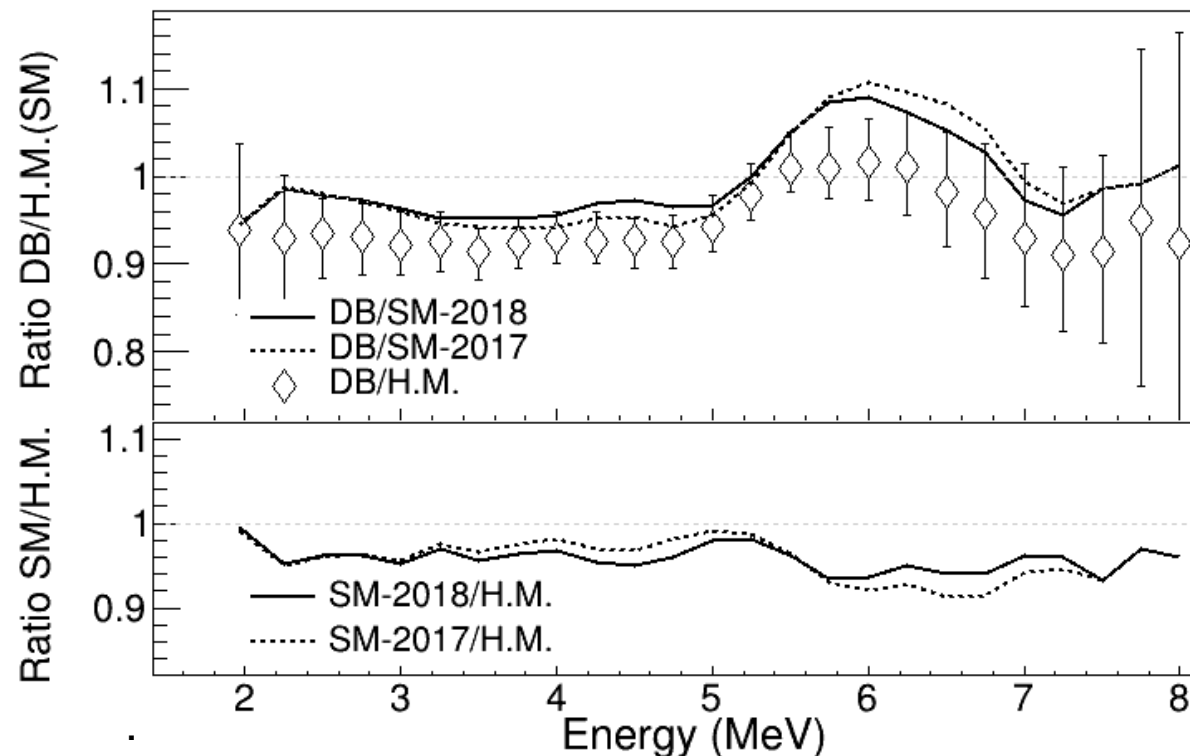
Kinetic E (MeV)	Nuclear databases	Forbid. treatment	AC,w corrections	Missing info.
2.00	1.2	0.2	0.1	10
2.25	1.3	0.2	0.2	10
2.50	1.3	0.1	0.3	10
2.75	1.3	0.1	0.3	10
3.00	1.4	0.4	0.4	10
3.25	1.6	0.7	0.5	10
3.50	1.7	0.1	0.5	10
3.75	1.9	1.3	0.6	10
4.00	2.2	1.6	0.6	10
4.25	2.5	1.6	0.7	10
4.50	2.8	1.4	0.8	10
4.75	3.2	1.0	0.8	10
5.00	3.8	0.5	0.9	10
5.25	4.4	0.2	0.9	10
5.50	5.2	0.2	0.9	15
5.75	6.1	0.2	0.9	15
6.00	7.1	0.2	1.0	15
6.25	8.0	0.3	1.0	15
6.50	9.0	0.4	1.1	15
6.75	10.1	0.4	1.1	15
7.00	10.9	0.5	1.1	20
7.25	11.0	0.7	1.1	20
7.50	10.7	0.8	1.1	> 20
7.75	11.1	0.8	1.2	> 20
8.00	13.3	1.2	1.3	> 20

- The agreement of the SM-2018 spectra with the shape of the H-M spectra is better than 5-10% !
- it is rather $\pm 2-3\%$ on the energy range dominating the flux
- Robustness of the SM w.r.t the choice of decay data data tested:
 - ⇒ remains robust in the 2 to 5 MeV range at the 2% level, i.e. a much better situation than the “10%” of missing information published in 2011 in Mueller et al.
 - ⇒ The level of agreement is confirmed by the 1.9% discrepancy with the DB flux
 - ⇒ will allow computing associated decay data uncertainties (only possible if Pandemonium effect is not too strong!)

TABLE II. Sources of errors in the ^{235}U electron spectrum as predicted by the *ab initio* approach. All errors are given in percent at 1σ (68% CL).

Comparison with Daya Bay results and H-M Predictions

M. Estienne et al. PRL 123, (2019) 022502 <http://arxiv.org/abs/1904.09358>



- Comparison of the full detected antineutrino energy spectrum obtained with the summation model, **without any renormalization**, with the measurements from Daya Bay.
- The **2018 data improve the agreement with Daya Bay** (ratio DB/SM closer to 1)

- Even with the inclusion of the 2018 TAGS data, the **bump is still there** i.e. for the moment, it still **cannot be explained** by ingredients of the nuclear databases.
- **With the SM model, no huge discrepancy in the flux w.r.t. DB for one specific fissioning nucleus: 2.5-3% for ^{235}U and ^{239}Pu (contrary to H.-M.) and about 1% for ^{238}U and ^{241}Pu**

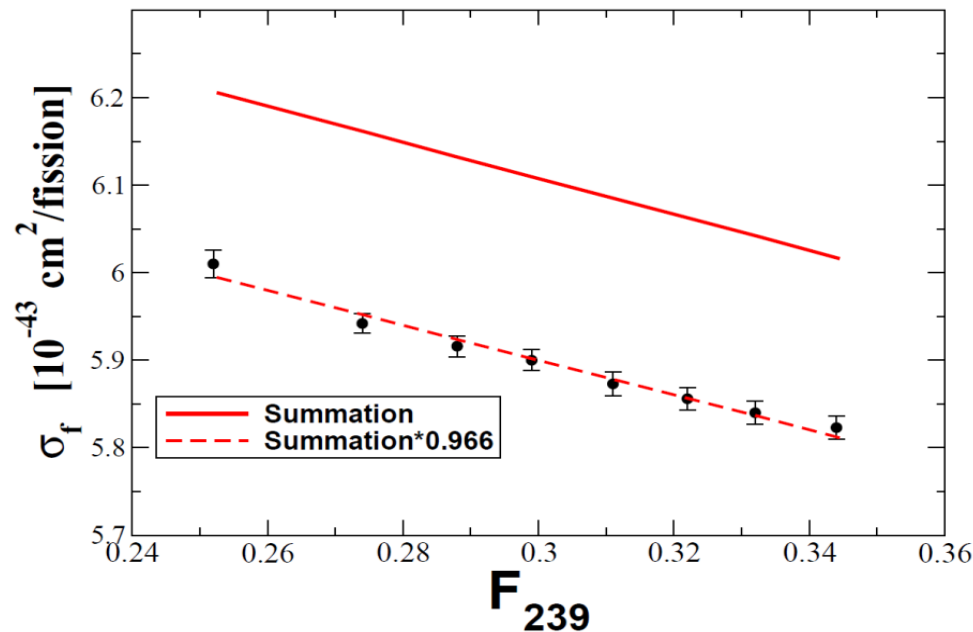
IBD Average Yields

	DB	SM 2018	SM 2017	SM 2012	SM from [42]	H-M
σ_f (10-43cm ²)	5.9±0.13	6.01	6.05	6.10	6.11	6.22±0.14
$\frac{d\sigma_f}{dF_{239}}$ (10-43cm ²)	-1.86±0.18	-1.82	-1.83	-1.87	-2.05	-2.46±0.06
σ_5 (10-43cm ²)	6.17± 0.17	6.28	6.31	6.38	6.49	6.69±0.15
σ_9 (10-43cm ²)	4.27± 0.26	4.42	4.44	4.47	4.49	4.36±0.11
σ_8 (10-43cm ²)	10.1±1.0	10.14	10.20	10.27	10.2	10.1±1.0
σ_4 (10-43cm ²)	6.04±0.6	6.23	6.27	6.29	6.4	6.04±0.6
σ_5/σ_9	1.445±0.097	1.421	1.421	1.427	1.445	1.53± 0.05

- The agreement of the individual contributions of ²³⁵U, ²³⁹Pu, ²⁴¹Pu and ²³⁸U with the detected antineutrino flux and of the slope of the IBD yield with the burnup with that measured by the DB experiment is improved by our new model.
- **With the SM model, no huge discrepancy in the flux w.r.t. DB for one specific fissioning nucleus: 2.5-3% for ²³⁵U and ²³⁹Pu (contrary to H.-M.) and about 1% for ²³⁸U and ²⁴¹Pu**

First Comparison with a SM model

A. C. Hayes et al. PRL 120 (2018) 022503



- Summation calculation by Hayes et al. compared with Daya Bay IBD yield evolution with ^{239}Pu fission fraction
- Compatible dependence of the flux vs F_{239} between the calculation and Daya Bay
- But, still a deficit observed in DB data but smaller than with converted model

➡ 3.5% deficit is still large enough to say that the reactor anomaly exists

IAEA Technical Meeting 2019

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Nathaniel Bowden
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Patric Huber
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Nathaniel Bowden

Technical Meeting on Nuclear Data for Anti-neutrino Spectra and Their Applications

23-26 April 2019, IAEA Headquarters, Vienna, Austria

The Nuclear Data Section of the International Atomic Energy Agency is holding a Technical Meeting on Nuclear data for anti-neutrino spectra and their applications, from 23 to 26 April 2019.

The idea is to bring together experts from the broad spectrum of physics, theory and measurements, related to anti-neutrino studies for basic sciences (mixing angle in neutrino oscillations) and for applications (reactor monitoring with anti-neutrino detection), to review the current status of:

- neutrino anomalies and the sterile neutrino hypothesis
- existing measurements of integral beta spectra
- recent Daya Bay, Double Chooz and Reno results on spectra measurements
- results from short baseline experiments Prospect, SoLid, Neutrino-4/DANSS, NEOS
- conversion method and uncertainties, corrections
- summation method and impact of nuclear data (beta decay data; fission yield data; uncertainties and correlations)
- nuclear data libraries (ENDF/B; JEFF; JENDL)

The goal is to (a) assess the sensitivity of the observations to uncertainties affecting large and short-baseline anti-neutrino measurements, (b) address the limitations and uncertainties of the theoretical methods (conversion vs summation), (c) estimate their dependence on the available data (beta spectra, decay data, fission yields), and finally (d) make recommendations for the existing measurements, theories and evaluations and e) new proposals for the future where needed.

The meeting will start on Tuesday 23 April in the afternoon, and finish on Friday 26th April again in the afternoon.

The meeting will include presentations from experts covering the above listed topics and discussions that will lead to a list of recommendations for the relevant scientific community. A summary report of the meeting will be published as an INDC(NDS) report.

A list of abstracts is given below. Presentations will be uploaded as they become available.

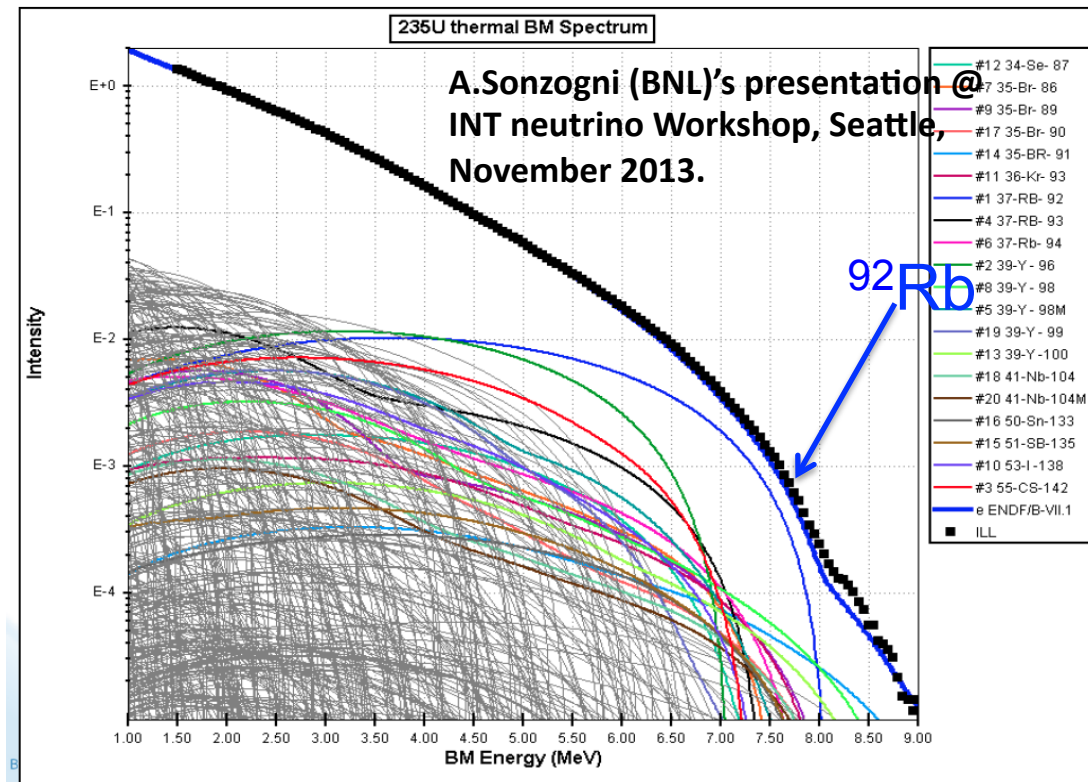
Preliminary Agenda

Abstracts

#	Author	Title	Link
1	P. Huber	Antineutrino spectrum prediction and nuclear data	DOC

A Reduced List of Important Contributors

- ✓ Example of ^{92}Rb : Candidate **Pandemonium** nucleus, GS-GS 1st forbidden transition with high I_b
- ✓ Large contribution in ^{235}U and ^{239}Pu ν spectra: $\sim 16\%$ of the ν spectrum emitted by PWRs in [5-8] MeV !!!



Our summation calculations give the following priority list:

TABLE I. Main Contributors to a standard PWR antineutrino energy spectrum computed with MURE using the summation method [12].

	4 - 5 MeV	5 - 6 MeV	6 - 7 MeV	7 - 8 MeV
^{92}Rb	4.74%	11.49%	24.27%	37.98%
^{96}Y	5.56%	10.75%	14.10%	-
^{142}Cs	3.35%	6.02%	7.93%	3.52%
^{100}Nb	5.52%	6.03%	-	-
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The number of contributors in these bins is small enough to give the hope to produce summation calculations with reduced systematic errors due to decay data at a relatively short time scale

M. Fallot et al. Phys. Rev. Lett. 109 (2012) 202504
A.-A. Zakari-Issoufou et al. PRL 115, 102503

A. Sonzogni et al. Phys. Rev. Lett. 116, 132502 (2016) &
Phys. Rev. C 98 041323(2018) (2018)

2 independent Summation Models in agreement

A Reduced List of Important Contributors

A.-A. Zakari-Issoufou, PRL 115, 102503 (2015)

TABLE I. Main contributors to a standard PWR antineutrino energy spectrum computed with the MURE code coupled with the list of nuclear data given in [12], assuming that they have been emitted by ^{235}U (52%), ^{239}Pu (33%), ^{241}Pu (6%) and ^{238}U (8.7%) for a 450 day irradiation time and using the summation method described in [12].

	4 - 5 MeV	5 - 6 MeV	6 - 7 MeV	7 - 8 MeV
^{92}Rb	4.74%	11.49%	24.27%	37.98%
^{96}Y	5.56%	10.75%	14.10%	-
^{142}Cs	3.35%	6.02%	7.93%	3.52%
^{100}Nb	5.52%	6.03%	-	-
^{93}Rb	2.34%	4.17%	6.78%	4.21%
^{98m}Y	2.43%	3.16%	4.57%	4.95%
^{135}Te	4.01%	3.58%	-	-
^{104m}Nb	0.72%	1.82%	4.15%	7.76%
^{90}Rb	1.90%	2.59%	1.40%	-
^{95}Sr	2.65%	2.96%	-	-
^{94}Rb	1.32%	2.06%	2.84%	3.96%

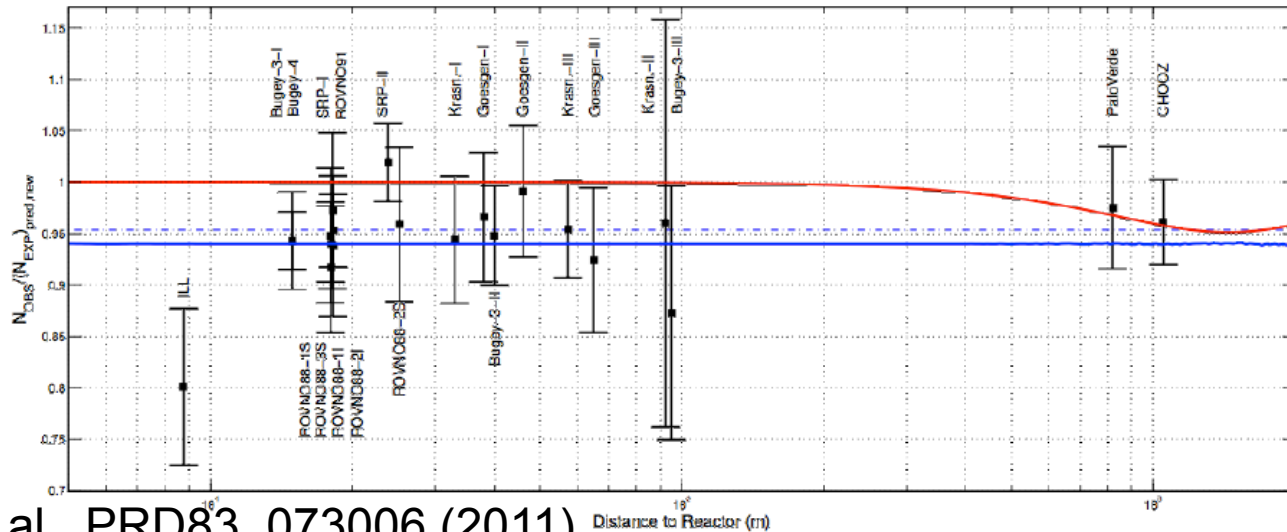
- Summation calculations give the following priority list of nuclei, with a large contribution to the PWR antineutrino spectrum in the high energy bins

The number of contributors in these bins is small enough to give the hope to produce summation calculations with reduced systematic errors due to decay data at a relatively short time scale

+ Quoting A. A. Sonzogni, E. A. McCutchan, and A. C. Hayes Phys. Rev. Lett. 119, 112501 (2017): « in order to confirm the existence of the reactor neutrino anomaly, or even quantify it, precisely measured electron spectra for about 50 relevant fission products are needed »

+ A. Sonzogni et al. Phys. Rev. Lett. 116, 132502 (2016) & Phys. Rev. C 98 041323(2018) (2018)

Reactor Anomaly (RAA)



G. Mention et al., PRD83, 073006 (2011)

#	result	Det. type	τ_n (s)	^{235}U	^{239}Pu	^{238}U	^{241}Pu	old	new	err(%)	corr(%)	L(m)
1	Bugey-4	$^3\text{He}+\text{H}_2\text{O}$	888.7	0.538	0.328	0.078	0.056	0.987	0.942	3.0	3.0	15
2	ROVNO91	$^3\text{He}+\text{H}_2\text{O}$	888.6	0.614	0.274	0.074	0.038	0.985	0.940	3.9	3.0	18
3	Bugey-3-I	$^6\text{Li-LS}$	889	0.538	0.328	0.078	0.056	0.988	0.946	4.8	4.8	15
4	Bugey-3-II	$^6\text{Li-LS}$	889	0.538	0.328	0.078	0.056	0.994	0.952	4.9	4.8	40
5	Bugey-3-III	$^6\text{Li-LS}$	889	0.538	0.328	0.078	0.056	0.915	0.876	14.1	4.8	95
6	Goesgen-I	$^3\text{He}+\text{LS}$	897	0.620	0.274	0.074	0.042	1.018	0.966	6.5	6.0	38
7	Goesgen-II	$^3\text{He}+\text{LS}$	897	0.584	0.298	0.068	0.050	1.045	0.992	6.5	6.0	45
8	Goesgen-II	$^3\text{He}+\text{LS}$	897	0.543	0.329	0.070	0.058	0.975	0.925	7.6	6.0	65
9	ILL	$^3\text{He}+\text{LS}$	889	≈ 1	—	—	—	0.832	0.802	9.5	6.0	9
10	Krasn. I	$^3\text{He}+\text{PE}$	899	≈ 1	—	—	—	1.013	0.936	5.8	4.9	33
11	Krasn. II	$^3\text{He}+\text{PE}$	899	≈ 1	—	—	—	1.031	0.953	20.3	4.9	92
12	Krasn. III	$^3\text{He}+\text{PE}$	899	≈ 1	—	—	—	0.989	0.947	4.9	4.9	57
13	SRP I	Gd-LS	887	≈ 1	—	—	—	0.987	0.952	3.7	3.7	18
14	SRP II	Gd-LS	887	≈ 1	—	—	—	1.055	1.018	3.8	3.7	24
15	ROVNO88-1I	$^3\text{He}+\text{PE}$	898.8	0.607	0.277	0.074	0.042	0.969	0.917	6.9	6.9	18
16	ROVNO88-2I	$^3\text{He}+\text{PE}$	898.8	0.603	0.276	0.076	0.045	1.001	0.948	6.9	6.9	18
17	ROVNO88-1S	Gd-LS	898.8	0.606	0.277	0.074	0.043	1.026	0.972	7.8	7.2	18
18	ROVNO88-2S	Gd-LS	898.8	0.557	0.313	0.076	0.054	1.013	0.959	7.8	7.2	25
19	ROVNO88-3S	Gd-LS	898.8	0.606	0.274	0.074	0.046	0.990	0.938	7.2	7.2	18